HYDRAULIC CONDUCTIVITY AND LEACHATE CHARACTERISTICS OF LIME STABILIZED FLYASH

A THESIS

Submitted towards partial fulfillment
of the requirements for the degree of

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IN

CIVIL ENGINEERING

WITH SPECIALIZATION IN

GEOTECHNICAL ENGINEERING

BY

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CERTIFICATE

This is to certify that the thesis entitled, "**Hydraulic Conductivity and Leachate Characteristics of Lime Stabilized Fly Ash**" submitted by **Sushree Sangita, Roll No: 612CE3008** in partial fulfillment of the requirement for the award of **Master of Technology (Research)** degree in **Civil Engineering** with specialization in **Geotechnical Engineering** at **National Institute of Technology Rourkela** is an authentic work carried out by her under our supervision and guidance. To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

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DECLARATION

This is to certify that project entitled **"Hydraulic Conductivity and Leachate Characteristics of Lime Stabilized Fly Ash"** which is submitted by me in partial fulfillment of the requirement for the award of **Masters of Technology (Research) in Civil Engineering, National Institute of Technology, Rourkela, Odisha** , comprises only my original work and due acknowledgement has been made in the text to all other materials used. It has not been previously presented in this institution or any other institution to the best of my knowledge.

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Sushree Sangita

Abstract

Coal based thermal power plants have been the backbone of a country due to its major contribution in electricity generation for the developmental purposes. Due to indomitable rise in demand of the electricity, the increase in generation of fly ash has become inevitable now-a-days. Moreover, the disposal of fly ash has become a major issue for coal based thermal power plants as it requires a vast disposal area and gives rise to a lot of problems like shortage of useful land, increase in disposal cost and dusting of atmospheric air. Fly ash generated from the coal fired thermal power plants is mostly sluiced into ash ponds by wet disposal method. This fly ash contains a number of soluble major and trace elements such as As, Fe, Cd, Hg, Zn, Pb and Cu, etc. There is possibility that leachate emanating from this fly ash bed may contaminate the ground and pose a threat to the human as well as aquatic life. Therefore, stabilization of fly ash by some chemical additives like lime/cement is an excellent method to mitigate the leachate characteristics of fly ash in addition to improve the strength and stability of the structure.

The leaching of metals mainly depends on two factor such as pH and hydraulic conductivity. The pH plays a pivotal role in reducing the concentration of the elements. Hydraulic conductivity also has a major effect in preventing the leachate from contaminating the ground water. If the material can be made less permeable, the leachate can be confined at the source of generation and thus the ground water can be protected from being contaminated.

A thorough study of the previous research works reveals that lime stabilization is an effective means of reducing the permeability and concentration of metals in the leachate emanating from ash ponds. In the present research work an effort has been taken to study the effect of lime on hydraulic conductivity and leaching characteristics of fly ash by varying the mix-proportion and curing period.

In addition to this, an experimental set up has been developed to investigate the efficacy of lime column in mitigating the leachate characteristics of compacted and sedimented ash beds.

The experiments were performed in two phases. At first, the compaction characteristics of fly ash mixed with different lime content such as 0%, 2%, 4%, 8%, 12% and 15% were found out from light and heavy compaction tests. The hydraulic conductivity and leachate characteristics of compacted fly ash-lime mixes were determined after 0, 7, 15, 30, 60 and 90 days of curing. All these samples were prepared corresponding to their respective MDD and OMC and cured for the specified curing periods as mentioned above. The concentration of the major and trace elements like Cu, Fe, Zn, Ca, Ni, Pb and Cr were found out by atomic absorption spectrometer. The effects of lime content and curing period on microstructure, morphology and hydration products in the stabilized specimens were studied by various microanalyses such as XRD and SEM tests.

Further, large scale laboratory models of sediment and compacted fly ash beds were prepared with a centrally installed lime column simulating a field condition as closely as possible. The samples were collected from various radial distances and depths after 7, 30, 90 and 180 days of curing period and subjected to different tests such as pH, and leachate analysis of different elements like Ca, Ni, Pb, Zn, Cu, Cr, and Fe. In addition to this, the hydraulic conductivity of treated ash deposit was measured by collecting undisturbed specimens from different radial distances and depths.

From compaction test results it is found that for light compaction test, with increase in lime content the OMC value increases up to 4% and thereafter, it decreases whereas in case of heavy compaction test, the OMC increases up to 2% lime addition and thereafter, it decreases. Similarly, the MDD in case of light compaction test decreases with increase in lime content up to 4% and thereafter it increases whereas in case of heavy compaction test the same value decreases up to 2% lime addition and thereafter, it increases.

The hydraulic conductivity value is found to depend on the lime content, compaction effort, and curing period. The samples containing higher doses of lime shows significant decrease in hydraulic conductivity value. It was found that at 90 days curing, it reduces about 10 times for samples compacted with light compaction energy whereas in case of heavy compaction, it decreases about 100 times than the unstabilized specimen. However, sample with no lime content showed marginal change in hydraulic conductivity value with curing period. XRD analysis shows the presence of compounds like ettringite, C-S-H and C-A-H gel which blocks the pore space and reduces the capillary voids. SEM analysis also confirms an interlocking network of hydration products which is responsible in reducing the hydraulic conductivity.

From the leachate analysis, it was observed that concentration of all elements was less than that of leachate sample of raw fly ash collected from acid digestion and extraction method. At 0 days curing the concentration of each metal (except Ca) is approximately same for different lime contents whereas at higher curing period, as the lime content increases, the concentration of metals in the leachate follows a decreasing trend. This is due to presence of alkaline medium which is unfavorable for metal precipitation and also due to encapsulation of metals by the hydration products. It is also observed that the concentration of all the metals was below the threshold limit of IS-10500 and WHO water quality standard.

The pH test results of the sample collected from sediment and compacted ash deposits show that the value is more in the sample collected adjacent to the lime column than that of the sample collected at a remote area from the lime column and also it increases with increase in depth. This is due to migration of lime to the periphery and downward direction of the tank. Moreover, it is observed that the pH value increases with curing period up to 180 days and thereafter, it decreases. Because with longer curing period lime is consumed in pozzolanic reaction which results in reduction of the pH value.

The permeability test result of lime column stabilized ash bed shows that during the early period of stabilization (30 days of curing) no significant variation in hydraulic conductivity value is observed in specimens collected at different locations (different radial distances and depths). However, as the curing period increases, the hydraulic conductivity follows an increasing trend with increase in radial distance whereas the same decreases with depth. In addition, it is also observed that as the curing period increases, a significant reduction in hydraulic conductivity occurs in all the layers of sedimented pond ash deposit.

The leachate analysis result shows that concentration of elements in the leachate sample collected from the test tank is much lower than the leachate sample extracted from raw fly ash. At early stage of curing the concentration of Ca is found to be more than that in the virgin fly ash, however at longer curing period, i.e at 365 days, the concentration of Ca is found to be decreased due to participation of lime in pozzolanic reaction. It is also observed from the results that the concentration of major and trace elements in the leachate sample collected adjacent to the lime column is lesser than that of the sample collected at the periphery of the test tank. This is due to higher pH value adjacent to the lime column as compared to remote areas. Moreover, the concentration of other elements in the leachate collected on 365 days curing is less than that of the sample collected on 90 and 180 days. This is due to the formation of hydration product such as C-S-H gel which encapsulates the elements and prevents leaching. The concentration of elements is found to be less than the threshold limit of WHO and IS-10500 water quality standard.

Thus, it is concluded that lime treatment is an effective means of reducing the hydraulic conductivity and concentration of metals in the leachate emanating from compacted as well as sedimented fly ash specimens.

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List of Abbreviation and Symbols

Abbreviations

Particular	**Description**
AAS	Atomic Absorption Spectrometer
C-A-H	Calcium Aluminate Hydrate
C-S-H	Calcium Silicate Hydrate
C-A-S-H	Calcium Aluminium Silicate Hydrate
DSC	Differential Scanning Calorimetry
EPA	Environmental Protection Agency
FA	Fly Ash
IS	Indian Standard
L/S	Liquid-to Solid Ratio
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
SEM	Scanning Electron Microscope
TCLP	Toxicity Characteristics of Leaching Procedure
TGA	Thermogravimetric Analysis
UCS	Unconfined Compressive Strength
WHO	World Health Organization
XRD	X-Ray Diffraction

Symbols

C_c	Coefficient of Curvature
C_u	Coefficient of Uniformity
k	Hydraulic Conductivity
L	Lime
R	Leachate- Load Ratio

CHAPTER-1

INTRODUCTION

1.1 AN OVERVIEW ON FLY ASH GENERATION

Coal based thermal power plants (TPPs) have been the backbone of a country due to its major contribution in electricity generation for the developmental purposes. With a stock of 70 billion tons of fossil fuel reserve, majority of TPPs (84%) are run on coal. About 260 million tons (MT) of coal (65% of annual coal produced in India) is being used by TPPs which ultimately results in generation of enormous quantity of fly ash in the country. At present, over 165 MT of fly ash is being generated by TPPs as a by- product of coal combustion and is predicted to cross 225 million tons by the year 2017. With the increase in generation of fly ash, its disposal has become a major issue for thermal power plants as it creates a lot of problems like shortage of usable land, increase in disposal cost, leaching of noxious heavy metals and dusting of atmospheric air. Generally, the fly ash is disposed of by using either dry or wet disposal method. Most of the power plants in India adopt wet disposal system where fly ash is being converted to slurry form and dumped in large settling pond called as ash pond which ultimately strikes negative impact on the environment. At present around 50,000 acres of land surface is occupied by ash ponds and continuously creating disposal and environmental problems. So the best way-out in order to get rid of these problems is its right application at the appropriate place by using available technologies.

1.2 FLY ASH UTILIZATION

Utilization of fly ash will not only help in mitigating the environmental problems, but also in preserving the conventional earth materials. Fly ash can be used in various sectors such as concrete manufacturing industries, structural fills for low lying areas, embankment and subgrade for highways, backfill in retaining structures, mine stowing, dam construction and dyke construction etc. Figure 1.1 shows the progressive generation and utilization of fly ash during the period from 1996-97 to 2012-13 and Figure 1.2 shows the quantity of fly ash utilization in various sectors during the year 2012-13.

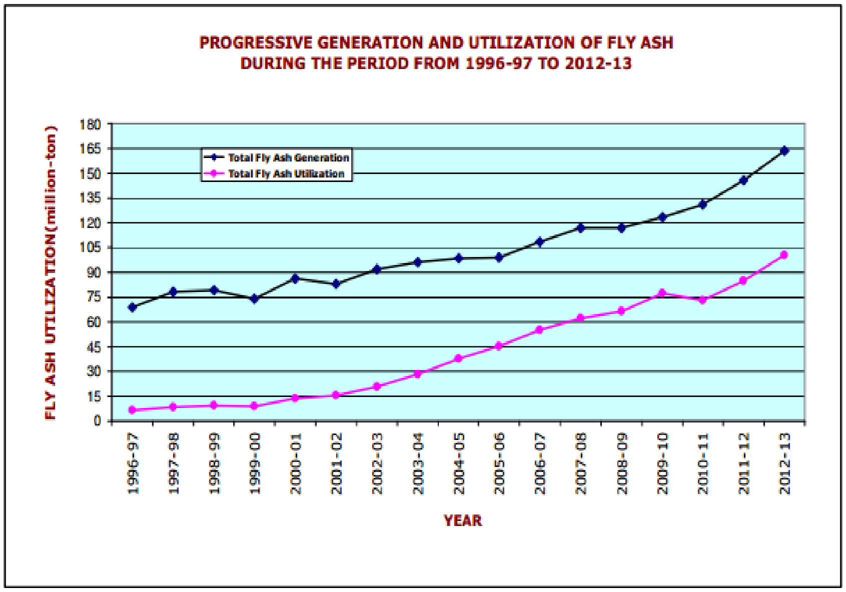


Figure 1.1. Progressive generation and utilization of fly ash in India

Source: (www.cea.nic.in)

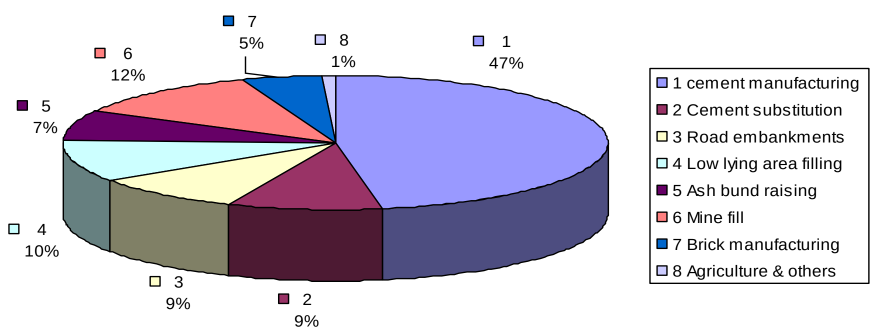


Figure 1.2. Utilization of Indian fly ash in different sectors (2012-2013)

Source: Central Electrical Authority (CEA) annual report

1.3 **ENVIRONMENTAL PROBLEMS ASSOCIATED WITH FLY ASH**

Generation of huge quantity of fly ash creates a lot of problems such as leaching and dusting. Due to the presence of finer particles and being light weight, it has the potential to be carried by air easily and pollute the environment which results in pulmonary diseases, including asthma and silicosis. Moreover, fly ash contains a lot of toxic heavy metals such as As, Be, Cd, Cr, Cu, Pb, Hg, Mo, Ni, V and Zn etc. [Adriano *et al* .(1980)]. These metals can leach out by the effect of rain and contaminate the ground water and pose a serious threat to the human as well as aquatic life. The concentration of metals in the leachate may vary according to the type and source of coal. Table 1.1 shows the concentration of trace elements in different types of coal in Indian context and Table 1.2 shows the average concentration of trace elements in Indian, USA and Australian coal.

However, it is observed from Table 1.3 that the concentration of major and trace element is quite more than the allowable and threshold limit of WHO and IS-10500 water quality standard. There is possibility that leaching of these metals to ground water may violate the statutory regulation for ground water pollution and can cause detrimental health problems to the human being as shown in Table 1.4. So, a major focus should be imparted on the environmental impact of fly ash utilization. Once the environmental impacts can be confidently predicted, a larger market can be encouraged to productively reuse fly ash.

The leaching of metals mainly depends on two factors such as pH and hydraulic conductivity. The pH plays a pivotal role in reducing the concentration of the elements. Hydraulic conductivity also has a major effect in preventing the leachate from contaminating the ground water. Fly ash stabilization by certain chemical additives may be an effective way-out to mitigate the effect of leaching and thus may help to keep the concentration of toxic metals within threshold limit of WHO and IS-10500 water quality standard.

Table 1.1. Concentration of trace elements in different types of Indian coal

Trace elements	Anthracite			High volatile Bituminous			Low Volatile Bituminous			Medium Volatile Bituminous			Lignite		
	Max ppm	Min ppm	Av ppm.	Max ppm	Min ppm	Av. ppm	Max Ppm	Min ppm	Av ppm	Max Ppm	Min ppm	Av ppm	Max Ppm	Min ppm	Av. ppm
B	130	63	90	2800	90	770	180	76	123	123	74	218	85	10	28
Co	165	10	81	305	12	64	440	26	172	290	10	105	40	2.1	11
Cr	395	210	304	315	74	193	490	120	221	230	36	169	90.8	5	70
Ga	71	30	42	98	17	40	135	10	41	52	10	-	16	0	6.7
Ge	20	20	-	285	20	-	20	20	-	20	20	-	10	0	3
Cu	540	96	405	770	30	293	850	76	379	560	130	313	67.1	1.6	20
Mn	365	58	270	700	31	170	780	40	280	4400	125	1432	228.4	10.5	100
Ni	320	125	220	610	45	154	350	61	141	440	20	263	0	100	45
Pb	120	41	81	1500	32	183	170	23	89	210	52	96	46.5	0	15
Sn	4250	19	962	825	10	171	230	10	92	160	29	75	35	0	12
V	310	210	248	840	60	249	480	115	278	860	170	390	278	0	86
Zn	350	155	-	1200	50	310	550	62	231	460	50	195	100	6	40

Reference: Vacovic (1983) and Chadwick (1987)

Table 1.2. Average concentration of trace elements in Indian, USA and Australian coal

Sl No	Element	Indian Average (ppm)	USA Average (ppm)	Australian Average (ppm)	Worldwide Average (ppm)
1	As	5.0	15	3	5
2	Hg	0.35	0.18	0.10	0.012
3	Cd	1.3	1.3	0.10	-
4	Ni	45	15	15	15
5	Co	11	7	-	5
6	Cr	70	15	6.0	10
7	Cu	20	19	1.5	15
8	Zn	40	39	25	50
9	Mn	100	100	-	50
10	V	86	20	20	25
11	Pb	15	16	10	25

Reference: Vacovic (1983) and Chadwick (1987)

Table 1.3. Allowable and threshold limits of concentration of metals in drinking water

Sl no	Elements	Content ranges in Indian fly ash (mg/kg)	WHO(1993)		IS-10500(1992)	
			Allowable limit (mg/l)	Threshold limit (mg/l)	Allowable limit (mg/l)	Threshold limit (mg/l)
1	As	2.3-6300	0.01	1.00	0.05	5.00
2	Ca	338-177,100	200	20000.00	200	20000.00
3	Cr	10-1000	0.05	5.00	0.05	5.00
4	Cu	14-2800	2.0	100.00	1.5	150
5	Fe	36-1333	0.3	30	0.3	30
6	Pb	3.1-50000	0.01	10.00	0.1	10
7	Hg	0.002-1.	0.001	0.1	0.001	0.1
8	Ni	6.3-4300	0.02	2.00	0.02	2
10	Zn	10-3500	3	300.00	5	500
11	Mg	116-60,800	150	15000.00	100	10000
12	Al	4615-24200	0.2	20.00	0.2	20

Table 1.4 Adverse effect of trace elements on environment

Sl No.	Trace elements	Health hazards
1	Pb	Tiredness, abdominal discomfort, irritability , anemia, brain swelling, kidney disease, cardio-vascular problems, nervous system damage
2	Hg	Itai-itai disease, hypertension, kidney damage, sterility among males developmental defects like reduced IQ and mental retardation
3	Cr	Stomach and intestinal ulcers, anemia, stomach cancer, lung cancer, asthma
4	As	Lung cancer, skin cancer, cardio-vascular and neurological disorders, affect the gastrointestinal tract respiratory tract, urinary tract,
5	Cu	headache, weakness Nausea, vomiting epigastric pain, diarrhea,
6	Ni	Cancers of nose and lungs
7	Zn	Vomiting and diarrhea, affect digestive mucous membrane
8	Se	Neurological disorder, impaired vision, paralysis
9	Sb	Eye, skin irritation, stomach pain, ulcers ,lung cancer
110	Cd	Kidney disease, Hypertension and lung cancer

Reference: Gottlieb et al. (2010)

By a thorough study of previous research works, it is perceived that most of the researchers have adopted lime stabilization technique to reduce the concentration of elements in the leachate but a limited attempt has been made to study the efficacy of lime column in mitigating the leachate characteristics of pond ash. In addition to this, the role of hydraulic conductivity and hydration products on leachability of elements are not investigated in detail. Moreover, mixing of lime in ash pond is practically not a feasible process. Keeping these aspects in mind an effort has been made to study the effect of lime column in mitigating the problems of leaching from the ash pond deposits through large scale laboratory model tests.

1.4 ORGANIZATION OF THE THESIS

The whole research work has been presented in six chapters. A brief description about the chapters is given below:

Chapter 1 describes some background knowledge on the fly ash generation, utilization and its effect on the environment. A brief description on the leachate characteristics of fly ash and the remedies to mitigate its effect is given.

Chapter 2 represents the critical review of relevant literatures including the effect of compaction effort, amount of lime, curing period on the hydraulic conductivity and leachate characteristics of fly ash. This also includes the efficacy of lime column in reducing the hydraulic conductivity and leachate characteristics of sediment pond ash deposits.

Chapter 3 present in details about the materials used, test procedure adopted for sample preparation, sampling scheme and details of experimental studies undertaken.

Chapter 4 delineates the effect of lime on the hydraulic conductivity and leachate characteristics of fly ash. The compaction characteristics of fly ash mixed with different lime content along with the hydraulic conductivity and leachate characteristics of the compacted fly ash specimens were determined after specified curing periods. The effect of lime and curing period on hydration products, microstructure and morphology in the stabilized specimens were studied by various microanalyses such as XRD, and SEM tests. A correlation is established between the hydraulic conductivity, leachate characteristics and the hydration products, microstructure.

Chapter 5 highlights the efficacy of lime column in reducing the leachate characteristics of sedimented and compacted fly ash bed. A lime column of 10cm diameter and 100cm depth was installed at the centre of the ash beds to study the effect of lime on leachate characteristics of pond ash. Radial and vertical migration of lime from the lime column was investigated by collecting leachate samples from different radial distances and depths at specified curing periods. At a given depth and radial distance, migration was studied by comparing the pH value of the treated fly ash with that of virgin fly ash specimen. The effect of lime was studied by performing leachate analysis and hydraulic conductivity test and comparing the values with that of the untreated fly ash.

Chapter 6 presents the experimental findings and future scope of the work.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

Fly ash is enriched with a number of toxic metals such as cadmium, chromium, nickel, lead, zinc, aluminum, iron, manganese, magnesium and silicon etc. There is a possibility that these undesirable components present in the fly ash leach out by the effect of rain and contaminate the ground as well as surface water. The leaching phenomenon is predominantly governed by two factors such as pH and hydraulic conductivity. Metal solubility generally decreases with increase in pH. Hydraulic conductivity also has a major effect in preventing the leachate from contaminating the ground water. If the material can be made impermeable, the leachate can be confined at the source of generation and thus, the ground water can be protected from being contaminated. Therefore, suitable chemical stabilization technique is adopted in order to control the migration of heavy metals to the surrounding. A good number of relevant literatures are available on the leaching behavior of major and trace elements which are cited in this chapter.

2.2. REVIEW OF LITERATURES

A good number of literatures are available on engineering properties of lime treated fly ash including the effect of lime on the leachate characteristics of fly ash deposits. The available literature are reviewed and presented in the following headings:

- Physical properties
- Chemical properties
- Leachate characteristics

2.2.1. Physical Properties

Bowders et al. (1990) investigated the effects of lime, cement and bentonite on the permeability and leaching of metals from the fly ash and found a reduced value of permeability (1.0E-08 cm/sec) by substituting lime or cement with bentonite. There was also a significant reduction in the concentration of trace elements due to addition of lime or cement.

Ghosh and Subbarao (1998) reported that the hydraulic conductivity of the fly ash specimens reduced substantially due to addition of lime and the concentrations of in the leachate were below threshold limits of water quality standard.

Ghosh and Subbarao (2001) used XRD, SEM and EDX techniques to gain information on the fly ash-lime interaction and reported that the reduction of permeability is due to the development of hydration products which blocks the capillary voids.

Kalinski and Yerra (2005) reported the hydraulic conductivity of compacted cement stabilized fly ash is affected compaction effort and curing.

Chand and Subbarao (2007) studied the efficacy of lime column in reducing the permeability and concentration of heavy metals emanating from pond ash deposits and reported that the lime column method was an effective means of reducing hydraulic conductivity and concentration of heavy metals emanating from pond ash deposits in addition to modifying other geotechnical parameters.

Pal and Ghosh (2011) studied the effect of compaction effort on hydraulic conductivity of class F fly ashes by preparing the samples corresponding to their light and heavy compaction energy. From the test results it was found that with increase in compaction effort, MDD increased and OMC of the sample decreased. A decreasing trend in hydraulic conductivity values were with the rise in MDD of the samples.

Cuisinier et al. (2011) reported that hydraulic conductivity of a soil was reduced significantly due to addition of lime.

Kishan et al. (2012) studied the leaching of metals by stabilizing fly ash with lime and/or gypsum and found a reduced value of hydraulic conductivity due to addition of these chemical additives.

Amiralian et al. (2012) studied effects of lime and fly ash in compaction properties of sand based on the seven specimens (i.e. 1 sand, 2 lime, 2 fly ashes and 4 mixture of lime-fly ash). The given result of lime and fly ash specimens illustrated that fly ash stabilization was more effective than lime treatment alone. However, utilization of combination of additives leads to optimum effect on compaction characteristics of sand.

Tran et al. (2014) studied the effects of lime treatment on the microstructure and hydraulic conductivity of compacted expansive clay and reported that the decrease in hydraulic conductivity in the cured specimens was due to the formation of cementitious compounds which clog the pores.

2.2.2. Chemical Properties

Shively et al. (1986) conducted sequential extraction test on Portland cement-based products containing metal sludge and reported that leaching of metals is dependent upon the pH.

Luxa'n et al. (1989) used several techniques like X-ray diffraction and infrared absorption spectroscopy and identified the formation of hydration products (C-A-H gel) due to fly ash - lime reaction.

Gould et al. (1989) reported that metal solubility generally decreases with increase in pH.

Xu and Sarkar (1991) used various techniques like XRD, SEM, and EDX to study the effect of lime and cement on the strength properties of fly ash and reported that the hydration products are formed due to fly ash-lime reactions and these are responsible for gaining of strength.

Cheng and Bishop (1992) performed sequential leaching extraction test on fly ash and found that leaching of metals occurs at low pH.

Webster and Loehr (1996) investigated on the leaching of elements like Cd and Pb from concrete products and reported that the reduced concentration of metals is due to presence of calcium matrix within the concrete which was responsible for reducing the concentration of cadmium and lead.

Fleming et al. (1996) studied the leach-ability of metals like Cd, Zn, Pb, Cr, Ag and Hg from fly ash generated by thermal power plant and a municipal waste incinerator by conducting column leaching experiments under acidic conditions and reported that extraction of metals depends upon pH value.

Bishop (1988) performed sequential extraction test to study the leaching of metals like chromium, cadmium and lead and reported that the reduction in concentration of metals was due to the encapsulation of metal ions by hydration products.

Sengupta and Miller (1999) investigated on the contaminants leaching out from the scrap tire material treated with a synthetic solution of varying pH and reported that the concentration of contaminants that leach out depended on the pH of the environment

Lau and Wong (2001) reported that leaching behavior of different element differs due to differences in elemental properties and pH of the solution.

Bin-Shafique et al. (2006) conducted various types of leaching tests on the fly ashes to study the leaching of chromium, cadmium, Selenium and silver. From the results it was found that the concentration of elements in the fly ash is greatly dependent upon pH of the material.

Jankowski et al. (2006) studied the leaching of metals like As, B, Mo and Se in fly ash generated from Australian power stations by conducting batch leaching test and reported that the pH of the leaching solution was the major factor which affects the migration of these trace elements in the fly ashes.

Ghosh and Subbarao (2006) reported that the leaching of metals reduces due to addition of chemical additives like lime and/or gypsum.

Wang et al. (2007) studied the effect of Calcium on arsenic adsorption onto coal fly ash by conducting batch leaching test and reported that addition of calcium significantly reduced the soluble arsenic ratio in the alkaline pH range.

Prasad and Mondol (2008) investigated on the heavy metals leaching in Indian fly ash and reported that maximum leachibility of all elements was found at pH of 2.

Sridevi et al. (2010) studied the leaching of lime from fly ash bed stabilized with varying percentage of lime 2 to 10% with 2% increment of lime and reported that the cumulative percentage of lime leached was negligibly small. For 10% lime content in the FAC, only 0.11% of lime was found to leach out. For lower lime contents the cumulative percentage of lime leached was even smaller than 0.11% and lime-stabilized FACs could be used in civil engineering applications such as pavements, foundations, embankments etc.

Vítková et al. (2010) studied the leaching characteristics of fly ash generated from a cobalt smelter using the pH-static leaching test (CEN/TS 14997, pH range 5-12) coupled with mineralogical investigation and speciation-solubility modelling. It was observed that the maximum leaching occurred at pH 5 and minimum at pH 12. The main solubility-controlling phases in this system were CaCO3 and CaSO4·2H2O.

Behera and Mishra (2012) studied the microstructural characteristics of low lime fly ash stabilized with lime by conducting XRD as well as SEM tests. The leachate analysis shows that the concentration of Ni, Cr and Pb in the leachate effluents were below threshold limits. The reduced concentration of elements is due to the development of hydration products.

Izquierdo and Querol (2012) reported that the amount of calcium plays a pivotal role on the pH of the fly ash. The mobility of most elements is greatly dependent upon the pH of the medium. The leaching of elements reduces due to encapsulation of metals by hydration products.

Guleria and Dutta (2013) studied the effect of treated tire chips on leaching characteristics of fly ash-lime-gypsum composite and found a reduced concentration of leaching metals.

Ozkok et al. (2013) studied the leaching behavior of arsenic, chromium, and copper from high-carbon fly ash–soil mixtures and reported that As and Cr (VI) are retained at acidic pH and leach more at pH >7. Significant leaching of Cu was only observed at pH<7.

2.2.3. Leachate Characteristics

Hajarnavis et al. (2000) studied the environmental impact of fly ash by collecting 32 number of fly ash samples from different thermal power plants located in various states and reported that total metal concentration was very high in most of the fly ashes. The wide variation in heavy metals was attributed to the quality of coal used in thermal power plant.

Choi et al. (2002) performed batch leaching tests to study the leaching characteristics of different types of fly ashes. It was found that the concentration of Si, Al and K was higher in anthracite coals than the sub-bituminous coals.

Sushil and Batra (2006) analyzed the content ranges of heavy metals like Pb, Cr, Cu, Ni, Zn,Co, and Mn in fly ash collected from different thermal power plants in India and from the test results, it was found that the concentration of Chromium and Zinc were highest whereas the concentration of Cobalt was lowest.

Sarode et al. (2010) studied the effect of cement on the leach-ability of heavy metals fly ash, bottom ash by toxicity characteristic leaching procedure (TCLP) and from the test results it was found that all the elements except Ni and Pb were slightly higher than the WHO water quality standard.

Lokeshappa and Dikshit (2012a) worked on single step extractions of metals in coal fly ash The evaluation of the optimum time for leaching of the toxic metals and metalloids present in the three fly ashes was determined using the single step extraction procedure.

Lokeshappa and Dikshit (2012b) studied on the leachate characteristics of both class c and class F laboratory scale ash ponds and found out that the concentration of metals like arsenic, chromium increased with time in case of class F ash whereas the concentration of all metals deceased in ash pond containing class C ash.

2.3. CRITICAL OBSERVATION

Scanning thorough the previous research works, it is perceived that most of the researchers have adopted lime stabilization technique to reduce the concentration of elements in the leachate but a limited attempt has been made to study the efficacy of lime column in mitigating the leachate characteristics of pond ash. In addition to this the role of hydraulic conductivity and hydration products on leachability of elements are not investigated in detail. Moreover, mixing of lime in ash pond is practically not a feasible process. Keeping these aspects in mind an effort has been made to study the effect of lime column in mitigating the problems of leaching from the ash pond deposits through large scale laboratory model tests.

2.4. OBJECTIVE AND SCOPE OF THE PRESENT WORK

The objective of the present research work is

- To reduce the concentration of major and trace elements in the leachate generated from fly ash deposit /construction site below threshold limit so as not to pollute the surrounding area and ground water.

- To confine the leachate to the source i.e. not allowing it to migrate from the point of disposal/in the area where fly ash is used as construction material to the surrounding**.**

The above objective is achieved by following means

2.4.1. Stabilization of Fly Ash by Lime

- Preparation of specimens by varying the fly ash and lime proportions (0%, 2%, 4%, 8%, 12%, and15%) and compacting them to their respective MDD and OMC obtained from light compaction and heavy compaction tests.

- Evaluation of hydraulic conductivity of specimens after curing periods of 0, 7,15,30,60 and 90 days.

- Analysis of major and trace elements by collecting leachate samples from permeability test specimens after specified days of curing.

- Analysis of cured sample by XRD and SEM techniques to study hydration products microstructure and morphology and to correlate with the hydraulic conductivity and leachate analysis results.

2.4.2. Stabilization of Sediment and Compacted Fly Ash Bed by Lime Column Technique

- Preparation of tank for sedimentation of fly ash slurry and installation of lime column.

- Determination of pH value and analysis of major as well as trace element concentration by collecting leachate samples from different radial distances(5cm, 15cm, 25cm and 35 cm and depths (10cm ,30cm, 50 cm, 70cm and 90cm) after curing periods of 30,90,180 and 365 days.

- Collection of undisturbed samples from different radial distances and depths and Evaluation of hydraulic conductivity after curing periods of 30, 90, 180 and 365 days.

- Analysis of test results.

CHAPTER 3

METHODOLOGY

3. 1. INTRODUCTION

The primary objective of this study is to reduce the concentration of metals in the leachate emanating from the fly ash bed and also to prevent the leachate effluents from contaminating the ground water so that a high level confidence can be built to reuse the fly ash as a sustainable and eco-friendly construction material in various geotechnical applications conserving the conventional construction metal. This chapter presents in details about the materials used test procedure adopted for sample preparation sampling scheme and details of experimental studies undertaken.

3.2. DETAILS OF TEST CONDUCTED

The experiments were performed in two phases. At first, the compaction characteristics of fly ash mixed with different percentage of lime content such as 0%, 2%, 4%, 8%, 12% and 15% were found out from light and heavy compaction tests. The hydraulic conductivity and leachate characteristics of compacted fly ash specimens were determined after 0, 7, 15, 30, 60 and 90 days of curing. All these samples were prepared corresponding to their respective MDD and OMC values and cured for the specified curing periods. The concentration of the major and trace elements like Cu, Fe, Zn, Ca, Ni, Pb and Cr in the leachate sample; collected on the above mentioned curing periods were found out by atomic absorption spectrometer. The hydration products and microstructure of the stabilized specimens were studied by using XRD and SEM analysis. Further, large scale laboratory models of sediment and compacted fly ash beds were prepared with a centrally installed lime column simulating a field condition as closely as possible. The samples were collected from various radial distances as well as depths after 7, 30, 90, 180 and 365 days of curing period and subjected to different tests such pH, and leachate analysis of different elements like Ca, Ni, Pb, Zn, Cu, Cr, and Fe. In addition to this, hydraulic conductivity of treated ash deposit was measured by collecting undisturbed specimens from different radial distances and depths.

3.3. MATERIALS

3.3.1 Fly Ash

Fly ash used in the experimental work was procured from RSP Rourkela. This is collected directly from hopper which in turn receives the fly ash from the electrostatic precipitator. The procured fly ash was stored in large bins before it was used for preparation of the test beds. It was completely in dry state. Its physical properties and chemical composition are given in Table3.1. The SEM image of fly ash is shown in Figure 3.1 which reveals that most of the particles are spherical structure with few irregular particles. The XRD analysis result of fly ash is shown in Figure 3.3 from which it is observed that it's major constituents of are silica, alumina and iron oxide. From energy dispersive X-ray analysis, it was found that calcium present in the fly ash is less than 20%. So, according to ASTM specification C 618-89 (1992), this fly ash belongs to a Class F category.

3.3.2 Lime

The lime used in this experimental investigation was procured from local market. From the SEM image as shown in Figure 3.2, it is observed that the particles of lime are irregular in shape. The XRD test result of lime sample is shown in Figure 3.4. From the figure it is observed that it's major constituents are CaO and $CaCO_3$. The purity of lime was found to be 90.2%. It also contains silica and other earth material in small quantity.

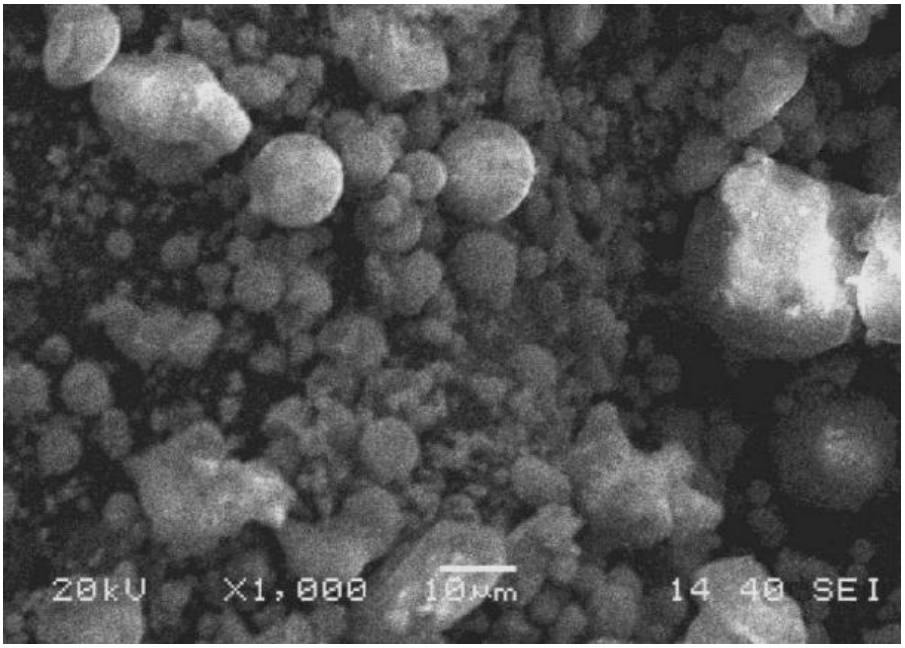


Figure 3.1. SEM image of RSP fly ash

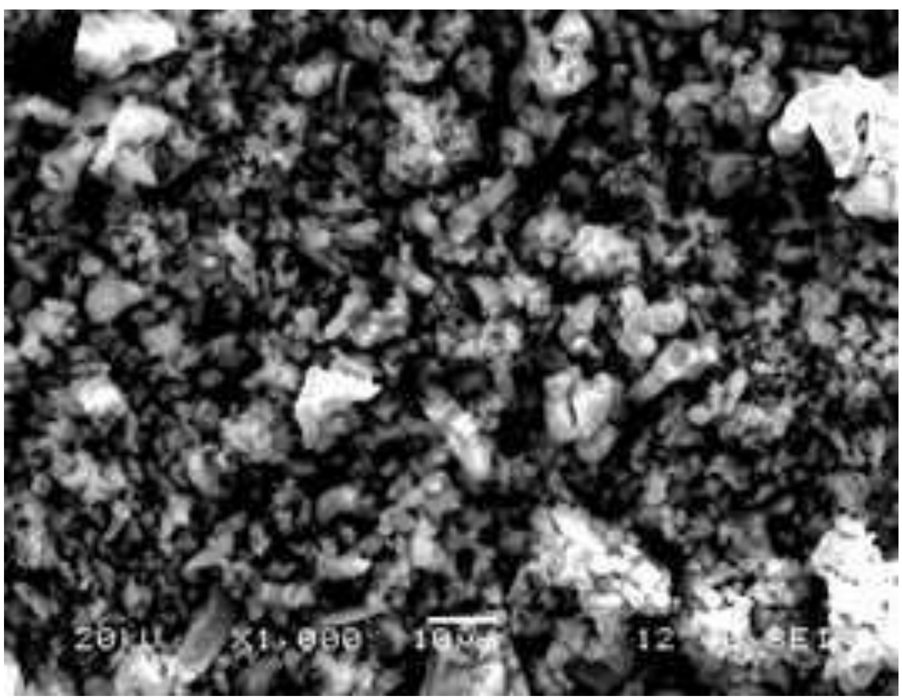


Figure 3.2. SEM image of lime

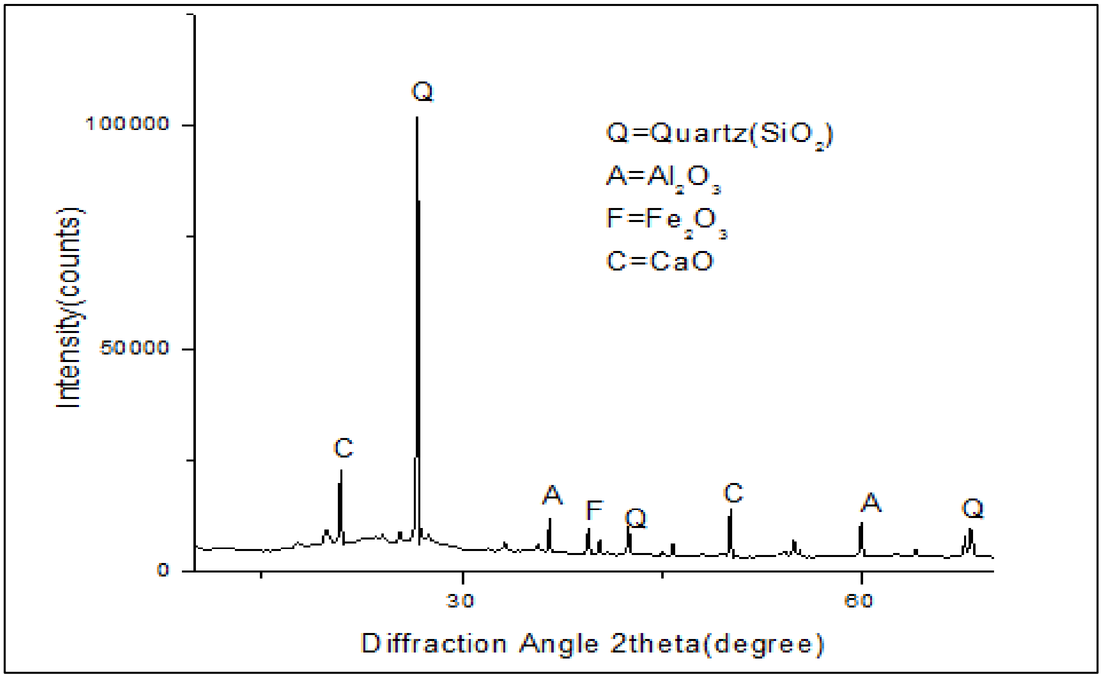


Figure 3.3 XRD analysis of raw fly ash

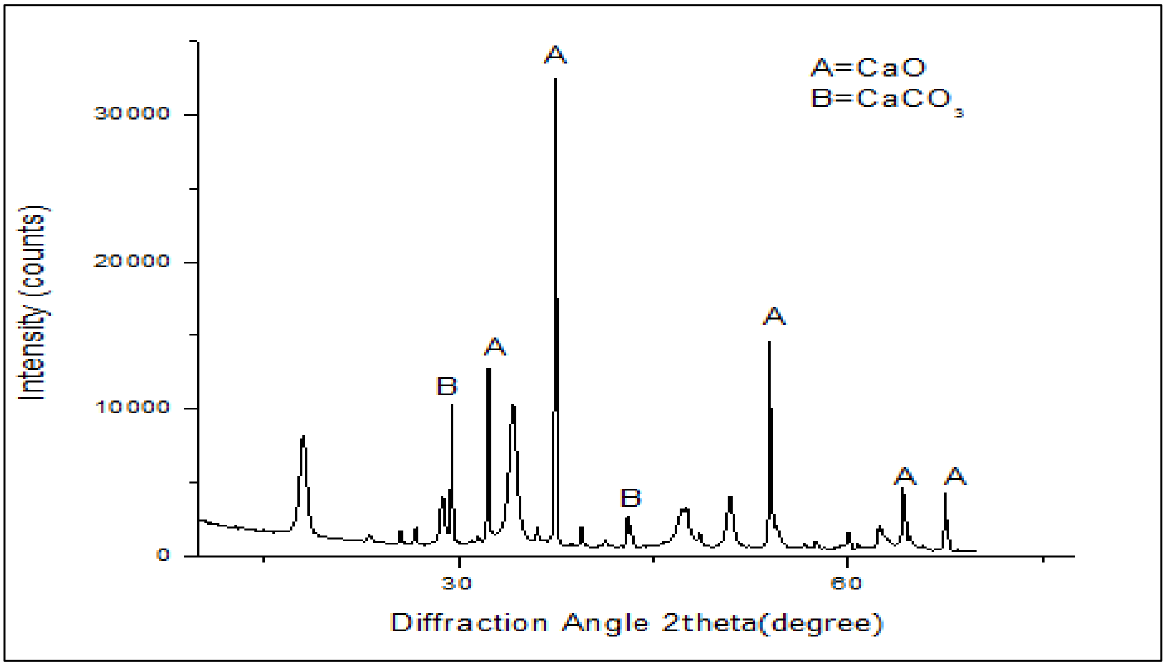


Figure 3.4 XRD analysis of lime

3.4. PROPERTIES OF RAW FLY ASH

3.4.1 Index Properties

3.4.1.1 Specific gravity

The specific gravity of fly ash was determined using density bottle method as per IS: 2720-1980 (Part 3) and was found to be 2.44.

3.4.1.2 Particle size distribution

Particle size distribution of fly ash was determined using both mechanical sieve and hydrometer analysis in accordance with IS: 2720-1985 (Part 4). Hydrometer analysis was conducted for the portions of fly ash passing through 75μm sieve and the mechanical sieve analysis for larger size particles. The gradation curve is shown in Figure 3.5. The uniformity coefficient (Cu) and coefficient of curvature (Cc) for Fly ash were found to be 8.34 & 2.08 respectively, indicating uniform gradation of samples.

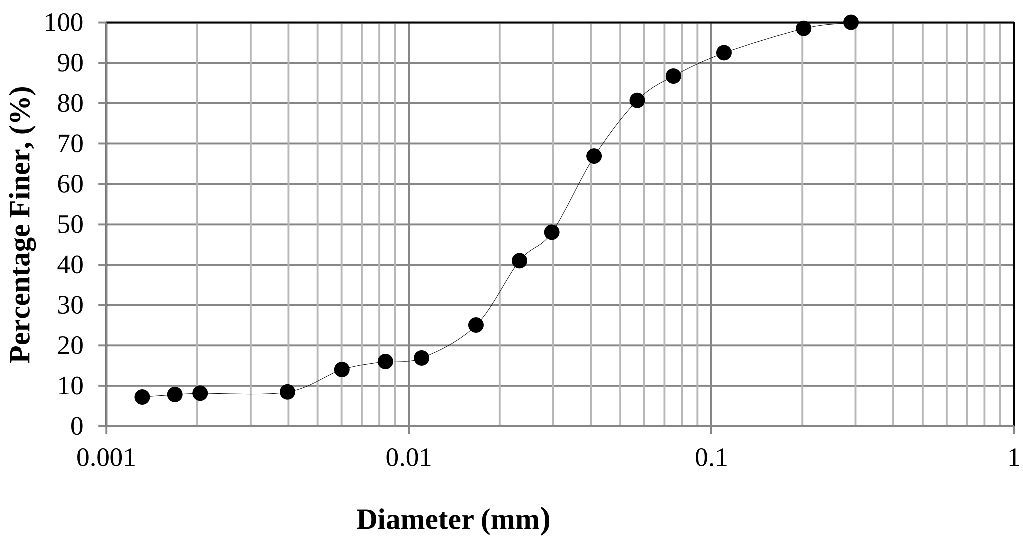


Figure 3.5 Grain size distribution curve of fly ash

3.4.1.3 Liquid limit

The liquid limit was determined by cone penetrometer method IS: 2720-1985 (Part 5) and was found to be 56.8%.

3.4.2 Chemical Properties

3.4.2.1 pH value

The pH of the virgin fly ash was determined according to IS: 2720- 1987 (Part 26). For this test, oven dried raw fly ash passing through 425 micron sieve was taken, mixed with water in liquid to solid ratio (L/S) = 2.5 and it was stirred in magnetic stirrer for 24 hours. Then the solution was filtered with Whatman 42 filter paper in order to make the sample free from suspended particles and the test was performed in a calibrated pH meter.

3.4.2.2 Total metal concentration and concentration of metals in leachate sample

The total concentration of major and trace elements present in the fly ash is determined by acid analysis (Figure 3.7) according to Environmental Protection Agency (EPA 3050B method). The leachate characteristics of raw fly ash are determined by extraction method (Toxicity Characteristic Leaching Procedure 1311 method). For this test, oven dried raw fly ash was taken and mixed with water in liquid to solid ratio (L/S) = 10 and it was stirred in electrical stirrer for 24 hours. Then it was filtered with Whatman 42 filter paper in order to make the sample free from suspended particles and then subjected to leachate analysis in atomic absorption spectrometer (Figure 3.8)

3.4.3 Engineering Properties of Fly ash

3.4.3.1 Compaction characteristics

Compaction curves of fly ash were obtained for both light and heavy compaction energies (Figure 3.6). The water content-dry density relationship for raw fly ash was determined from light and heavy compaction test according to the procedure prescribed in IS: 2720-1980(Part VII) and IS: 2720-1983(Part 8) respectively. The OMC values for light and heavy compaction test were found to be 38.74% and 32.29% respectively. The MDD values were found to be 1.16 and 1.28g/cc respectively.

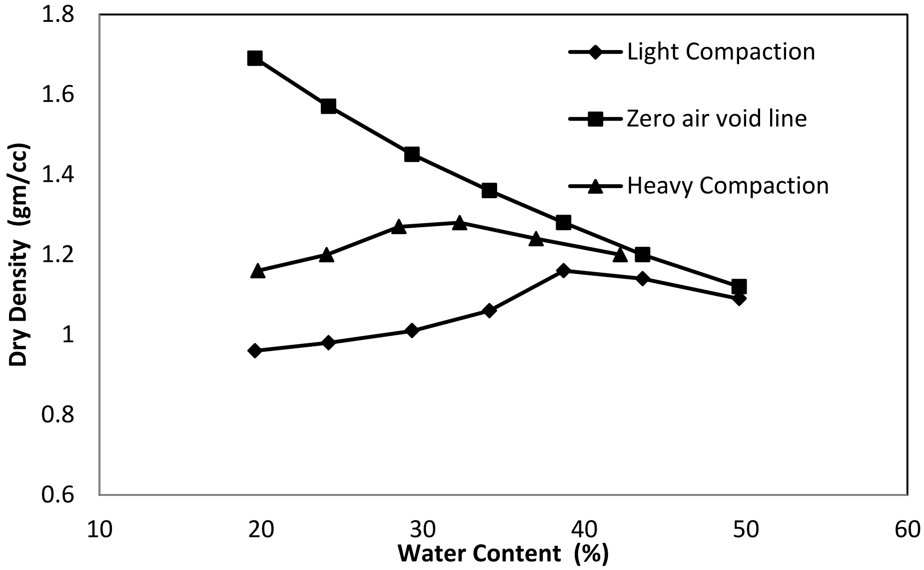


Figure 3.6 Compaction curve of RSP fly ash

3.4.3.2 Unconfined compressive strength (UCS Value)

The UCS tests were conducted according to IS: 2720-1991(Part 10). Cylindrical specimens of 100 mm in height and 50 mm diameter were prepared corresponding to MDD at OMC by static compaction method. For this test required quantity of dry fly ash was added with water to bring it to OMC and compacted in a constant volume mold. The samples were ejected from the mold and tested under an axial strain rate of 1.2mm/min. The UCS value was found to be 180kPa.

3.4.3.3 Shear parameters

The shear strength parameters of fly ash specimens were determined as per IS: 2720-1986 (Part 13). The undisturbed samples were collected from a specimen which was pre-compacted to MDD at OMC by inserting sampling device of size 60mm×60mm×25mm and the extra portions are trimmed. All the specimens were sheared at a rate of 0.2 mm/ min in a motorized direct shear machine. The unit undrained cohesion and angle of internal friction of fly ash were found to be 0.04 kg/cm ^{2} and 44^0 respectively.

Table 3.1 Properties of RSP fly ash

Physical Properties of Fly Ash		Chemical Composition	
Properties	Value	Constituents	Percentage
Specific gravity	2.44	SiO_2	59.2
Dry density	1.16 gm/cc	AL_2O_3	17.9
OMC	38.7%	Fe_2O_3	9.5
Liquid limit	56.8%	CaO	3.2
Cu and Cc	8.34and 2.08	MgO	1.3
Cohesion	0.04kg/cm^2	SO_4	1.2
Angle of internal friction	44^0	Unburnt carbon	7.0
Hydraulic conductivity	4.25X10^{-5} cm/sec	Others	0.7

3.5. EXPERIMENTAL STUDY

3.5.1 Procedure for Lime-Mixed Fly Ash

3.5.1.1 Laboratory compaction test

In this study both light compaction and heavy compaction tests were performed with different combination of fly ash and lime to determine OMC and MDD values of the fly ash lime mixes. In total 12 numbers of samples (six each for light and heavy compaction) were prepared by varying lime content as 0%, 2%, 4%, 8%, 12% and 15% of the dry mass of fly ash. In order to conduct compaction test on fly ash-lime mixes dry fly ash and lime were mixed in the mechanical mixture for a period of 3 minutes to bring homogeneity of sample and then required amount of water was added and mixing operation continued by hand to ensure uniform distribution of water. The samples were subjected to compaction tests without any further delay. The OMC and MDD values for all the samples were determined from the compaction curves and given in Table 3.2. For this IS: 4332(Part III) 1967 was followed instead of IS: 2720 (Part VII or Part VIII). As fly ash particles are cenosphere its compacted dry density was found to be much lower than the conventional earth material.

Table 3.2 OMC and MDD values of fly ash-lime mixes

Mix Proportions	Light compaction test		Heavy compaction test	
	OMC (%)	MDD (gm/cc)	OMC (%)	MDD (gm/cc)
FA+0%L	38.74	1.160	31.00	1.284
FA+2%L	40.38	1.130	36.88	1.259
FA+4%L	41.20	1.128	36.50	1.250
FA+8%L	38.62	1.140	32.57	1.290
FA+12%L	38.00	1.160	30.80	1.324
FA+15%L	37.92	1.170	30.50	1.330

3.5.1.2 Hydraulic conductivity

In total twelve numbers of permeability samples (6 numbers of samples compacted with light compaction and rest 6 numbers of samples compacted in heavy compaction energies) were prepared with different combination of fly ash and lime and compacted by means of hydraulic jack to their respective MDD at OMC value obtained from light and heavy compaction tests. The permeability tests were performed according to the procedure prescribed in IS: 2720-1986 (Part 17) in a constant head permeameter (Figure 3.5 and 3.6). The specimens were then saturated and the same was allowed to cure in ambient temperature (average value of 27^0C) for specified curing periods. The coefficient of permeability of fly ash specimens treated with different lime contents were evaluated after curing periods of 0, 7, 15, 30, 60 and 90 days. Further, the effluents coming out from the permeability mold at 0 and 90 days of curing were collected in sampling bottles and were tested for the concentration of different elements in an atomic absorption spectrometer. The pH value of the leachate samples collected from the permeability test on 0 and 90 days of curing were also determined and reported.

Figure 3.5 Permeability test set up **Figure 3.6** Constant head permeameter

3.5.1.3 Leachate analysis

The leachate samples were collected from the permeability molds after curing periods of 0 and 90 days in order to study the variation of leachate concentration in fly ash specimens. The samples are filtered with whatman 42 No. filter paper in order to make the sample free from suspended particles and then subjected to leachate analysis. Before filtration the sample the funnel, beaker and the sample storing bottles are washed with dilute nitric acid and later with distilled water.

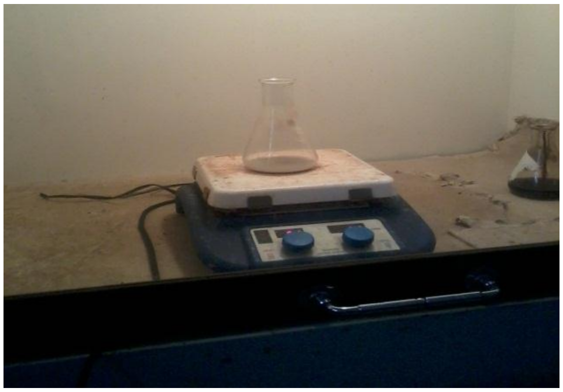


Figure 3.7 Acid digestion in fume hood **Figure 3.8** Atomic absorption spectrometer

3.5.1.4 Hydration products and microstructure analysis

The formation of hydration products and microstructure in cured specimens were studied by different methods likes X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) respectively. The XRD tests were done to find out the different phases of hydration peaks that appeared in the specimens after specified days of curing. This is performed with the help of X-ray diffractometer (model Rigaku, Ultima IV) and image shown in Figure 3.10. After the specified curing periods the samples are collected and soaked in acetone to stop further hydration. These samples (Figure 3.9) were ground to size less than 75µm before the tests. The analysis was done between the scanning range of 7-70^{o} with a, scanning rate 5^{o}/min.

Figure 3.9 Specimens used for XRD **Figure 3.10** Rikagu Ultima-IV X-ray diffractometer

The microstructure of the cured specimens was studied with the help of SEM analysis. The test was performed by using JEOL JSM-6480LV SEM, equipped with an energy dispersive detector of Oxford data reference system as shown in Figure 3.11. Before the test the samples are coated in a coating instrument (Figure 3.12). The coating was done at the rate of 20mA/120sec. Micrographs were taken at accelerating voltage of 20kV for the best possible resolution from the specimen.

Figure 3.11 JEOL-JSM-6480 LV SEM **Figure 3.12** Instrument used for coating the sample

3.5.2 Procedure for Lime Column Experiments

3.5.2.1 Preparation of sediment and compacted fly ash beds

Figure 3.14 and 3.16 shows the test set up for sedimentation of ash slurry which consists of a large circular galvanized iron tank of 105cm diameter and 120cm height open at the top with a drainage arrangement at the base. About 1 ton of fly ash sample was used and the amount of water required for the flow-able fly ash slurry was determined from step-by-step water addition, and mixing of fly ash. The optimum moisture content without bleeding of water from fly ash was based on eye judgment and it was found to be 75%. The slurry was prepared at this moisture content and placed in the tank. Figure 3.13 shows the placing of fly ash slurry in the test tank. Before placing slurry in the test tank, a cylindrical steel casing of 10cm dia and 100cm height, wrapped with fiber mesh of small aperture was placed at the middle of test tank. In addition to this fly ash beds were also prepared at MDD and OMC value. For this about 1 ton of fly ash sample was taken and compacted to maximum dry density (1.16gm/cc) at optimum moisture content (38.7%). After mixing, the sample was placed in the tank by 10 equal layers and tamped with a large hammer so that the compacted fly ash sample could be placed uniformly throughout the tank. Similar arrangements were also made here for placing the lime column.

3.5.2.2 Installation of lime column

At the end of the initial sedimentation period of one month, the lime column was installed at the center of the ash beds. The quantity of lime required for installing the lime column was 10kg. The required quantity of lime was taken and it was divided into10 equal parts after placing each part, the layers are tamped with a small hammer. Thus, a lime column of 10 diameter and 100cm height was installed at the middle of the ash beds.

3.5.2.3 Installation of temperature sensors

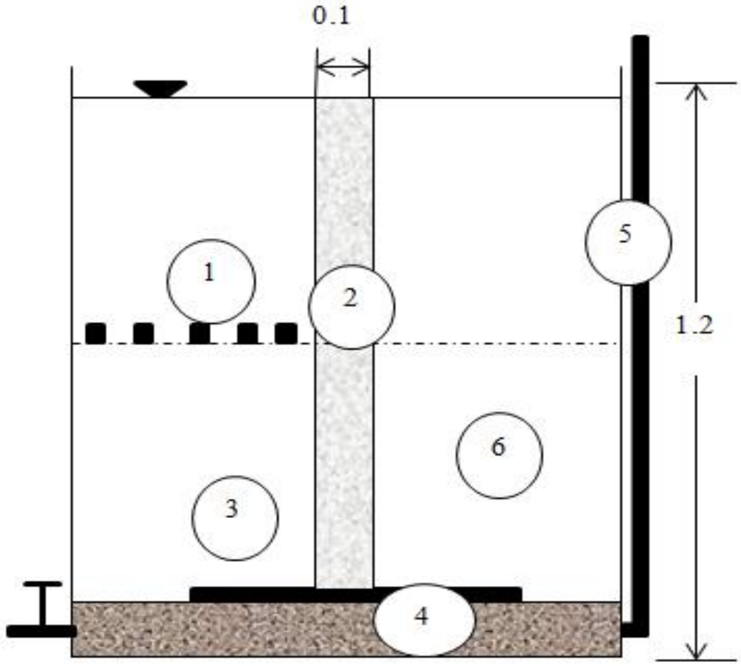
Temperature sensors are located at a depth of 0.5m from top of the fly ash bed in radial direction with c/c spacing of 0.1 m. In total five numbers of temperature sensors were placed in each testing tank. A multi-channel temperature recorder was used to note the temperature of the ash bed at different times and locations. These sensors were used in order to observe the difference in ambient temperature and temperatures at different locations inside the tank. This also measures the variation of temperature at various locations inside the tank after the installation of lime column. The sensors reveal that the temperature is higher at the locations near to the lime column as compared to the remote locations inside the fly ash bed initially after the installation of lime column. However, with passage of time no significant variation of temperature at different locations was observed.

3.5.2.4 Sampling program

Stabilized fly ash samples were collected after 30 days, 90 days, 180 and 365 days curing from different radial distances and depths and subjected to various tests. The samples were collected from four radial distances, i.e. 5cm, 15 cm, 25cm and 35cm and at 5 different depths i.e. 10cm, 30cm, 50cm, 70cm, and 90cm (Figure 3.18 and 3.19). For leachate analysis, 5 nos of steel hollow pipes of 1cm diameter, length varying from 10 to 90 cm are inserted with c/c spacing of 8 cm at a radial distance of 25 cm from the center of the test tank (Figure 3.17). In addition, another 4 numbers of similar pipes having length 50cm are inserted at four different radial distances for collecting leachate samples from a depth of 50cm. The detail positions for leachate sample collection are shown in Figure 3.15.

Figure 3.13 Placing of fly ash slurry in test tank **Figure 3.14** Sedimentation of fly ash

Figure 3.15 Sampling locations in the test tank for pH and leachate analysis



1-Temperature sensors, 2-Lime column, 3-Base plate, 4-Sandbed, 5-Stand pipe, 6-Fly ash bed

Figure 3.16. Details of test tank and its components

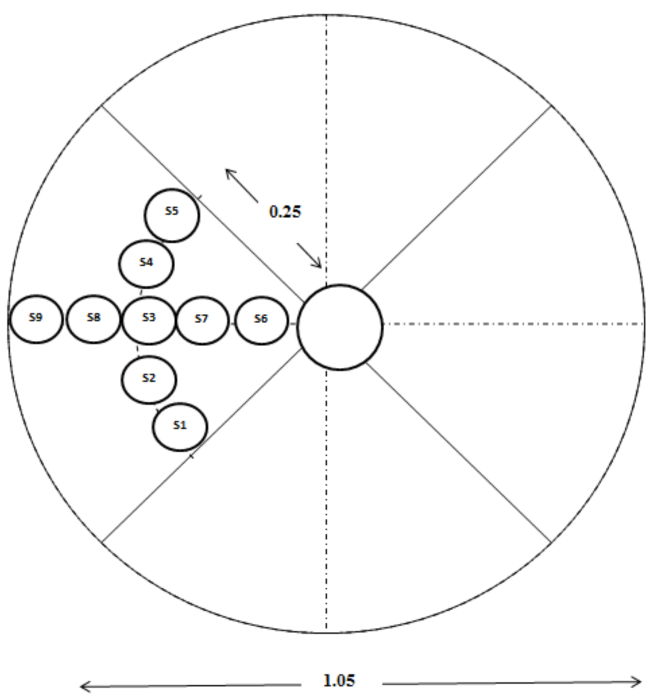


Figure 3.17. Plan of the test tank showing locations for collection of leachate samples

All dimensions are in m

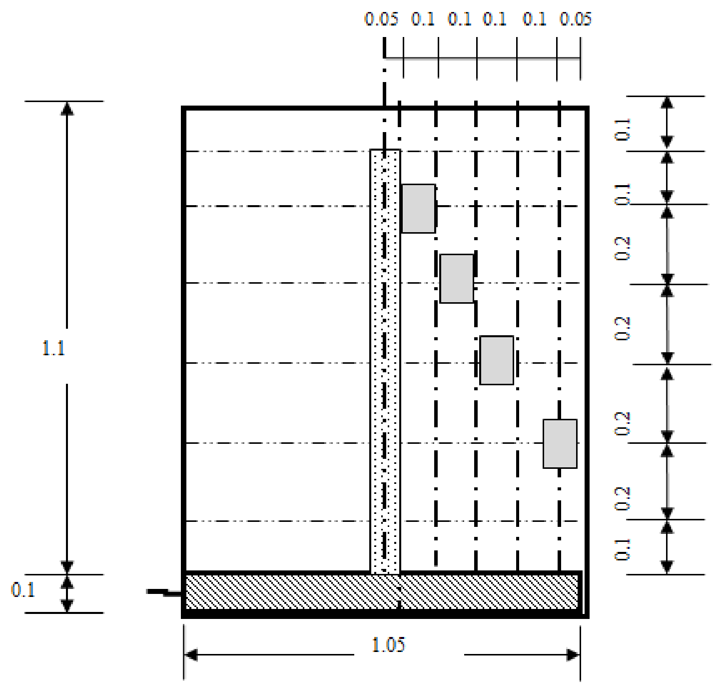


Figure 3.18. Elevation of the test tank showing locations for collection of samples for determination of hydraulic conductivity

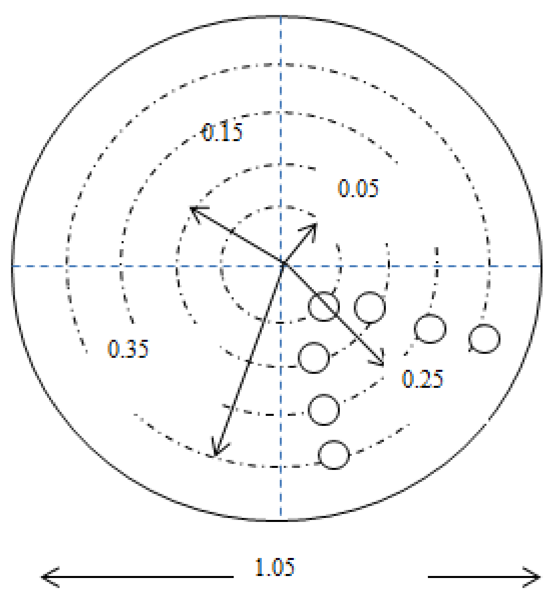
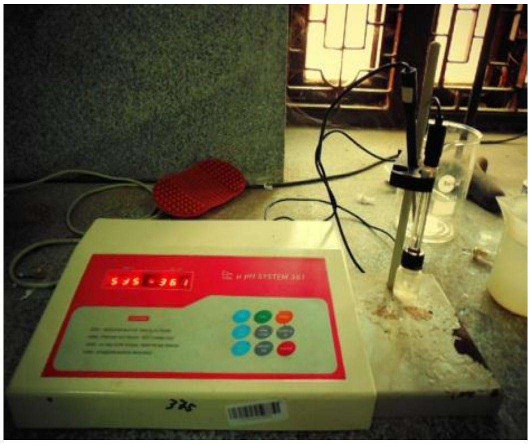


Figure 3.19. Plan of the test tank showing locations for collection of samples for determination of hydraulic conductivity

3.5.2.5. Details of test conducted

3.5.2.5.1 pH test

In order to know the variation of pH in the test tank, water samples are collected from different radial distances and depth of the sediment ash deposits after specified periods and stored in bottles for pH test. Then it was filtered with Whatman 42 filter paper and tested in a calibrated pH meter (Sony µ pH system 361) as shown in Fig. 3.20. During the test care is taken to see that the electrode of pH meter is immersed in the solution.



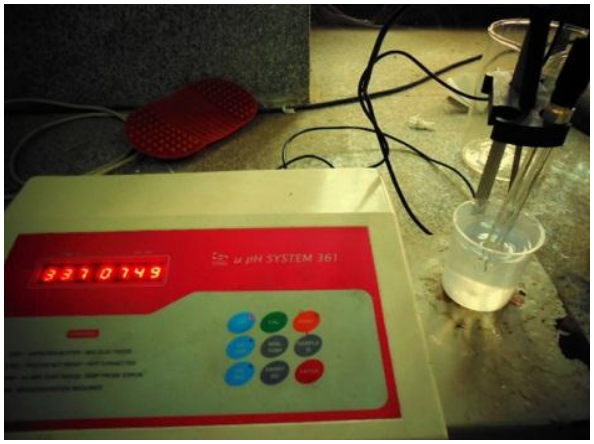


Figure 3.20. pH meter used for measuring the pH of the samples

3.5.2.5.2. Leachate analysis

The total concentration of major and trace elements present in the fly ash is determined by acid analysis according to Environmental Protection Agency (EPA 3050B method). The leachate characteristics of raw fly ash are determined by extraction method (Toxicity Characteristic Leaching Procedure 1311 method). In this method oven dried raw fly ash was taken with liquid to solid ratio (L/S) = 10 and it was stirred in magnetic stirrer for 24 hours. Then it was filtered with Whatman 42 filter paper in order to make the sample free from suspended particles (Figure 3.21) and then subjected to atomic absorption spectrometer (AAS) test. Before filtration of the sample all the glass wares such as funnels, beaker as well as the sample storing bottles (Figure 3.22) are rinsed with dilute nitric acid and later with distilled water. In order to know the leachate effluent characteristics of lime column treated ash, samples are collected from the test tank at various radial distances as well as depths after specified curing periods and the concentration of the elements like Cu, Fe, Ca, Ni, Pb, Cr and Zn were found out by AAS (Perkin Elmer).

Figure 3.21 Filtration of sample for AAS test

Figure 3.22. Sample used for AAS test

3.5.2.5.3. Hydraulic conductivity

The permeability of test specimens was performed according to the procedure prescribed IS: 2720-1987 (Part 36) using a constant head permeameter. In order to know the hydraulic conductivity of stabilized fly ash specimens, the samples were collected from different radial distances as well as different depths after specified days of curing with the help of the sampling tube. Then it was transferred into the permeability mold. Before transferring the sample into the permeability mold, sampling tubes are leveled at both the ends and the bottom of the permeability mold is covered with filter paper. Then the sample is transferred carefully without any disturbance. Another filter paper is placed at the top. Then the molds were fitted well and placed in position. Before conducting the test, it is ensured that the flow pipe is air free. If not, the air is removed by pulling the air vent. Tap water was allowed to flow though the sample and saturate it well and after some time effluents coming from the outlets of hydraulic conductivity molds were collected in sampling bottles and time taken in collecting the sample was noted.

Table 3.3. Hydraulic conductivity of sediment pond ash bed (in cm/sec) on 90 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$1.5X10^{-5}$	$2.4X10^{-5}$	$2.6X10^{-5}$	$2.68X10^{-5}$
30	$4.8\ X10^{-5}$	$6X10^{-5}$	$6.9X10^{-5}$	$7.6X10^{-5}$
50	$4X10^{-5}$	$3.7X10^{-5}$	$4.1X10^{-5}$	$5.9X10^{-5}$
70	$2.2X10^{-5}$	$2.8X10^{-5}$	$2.9X10^{-5}$	$3.14X10^{-5}$

Table 3.4. Hydraulic conductivity of sediment pond ash bed (in cm/sec) on 180 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$1.1X10^{-5}$	$1.5X10^{-5}$	$1.7X10^{-5}$	$2X10^{-5}$
30	$1.73X10^{-5}$	$1.9X10^{-5}$	$2.5X10^{-5}$	$2.7X10^{-5}$
50	$1.36X10^{-5}$	$1.8X10^{-5}$	$2.1X10^{-5}$	$2.5X10^{-5}$
70	$1.21X10^{-5}$	$1.5X10^{-5}$	$1.9X10^{-5}$	$2.3X10^{-5}$

Table 3.5. Hydraulic conductivity sediment pond ash bed (in cm/sec) on 365 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$2.26X10^{-6}$	$2.33X10^{-6}$	$2.49X10^{-6}$	$2.7X10^{-6}$
30	$2.56X10^{-6}$	$2.6X10^{-6}$	$2.7X10^{-6}$	$2.96X10^{-6}$
50	$2.49X10^{-6}$	$2.58X10^{-6}$	$2.64X10^{-6}$	$2.91X10^{-6}$
70	$2.44X10^{-6}$	$2.51X10^{-6}$	$2.59X10^{-6}$	$2.88X10^{-6}$

Table 3.6. Hydraulic conductivity of compacted pond ash bed (in cm/sec) on 90 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$2.43X10^{-5}$	$2.68X10^{-5}$	$2.79X10^{-5}$	$2.92X10^{-5}$
30	$2.15X10^{-5}$	$2.40X10^{-5}$	$2.60X10^{-5}$	$2.66X10^{-5}$
50	$1.75X10^{-5}$	$2.05X10^{-5}$	$2.21X10^{-5}$	$2.56X10^{-5}$
70	$1.50X10^{-5}$	$1.66X10^{-5}$	1.95X10-5	$2.21X10^{-5}$

Table 3.7. Hydraulic conductivity of compacted pond ash bed (in cm/sec) on 180 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$2.21X10^{-5}$	$2.32X10^{-5}$	$2.48X10^{-5}$	$2.64X10^{-5}$
30	$1.83X10^{-5}$	$1.96X10^{-5}$	$2.21X10^{-5}$	$2.32X10^{-5}$
50	$1.50X10^{-5}$	$1.68X10^{-5}$	$1.70X10^{-5}$	$1.85X10^{-5}$
70	$1.21X10^{-5}$	$1.39X10^{-5}$	$1.46X10^{-5}$	$1.71X10^{-5}$

Table 3.8. Hydraulic conductivity of compacted pond ash bed (in cm/sec) on 365 days curing

Depth (cm)	Radial distance (cm)			
	5 cm	15cm	25cm	35cm
10	$1.96X10^{-6}$	$1.85X10^{-6}$	$2.84X10^{-6}$	$3.72X10^{-6}$
30	$1.50X10^{-6}$	$1.77X10^{-6}$	$2.43X10^{-6}$	$2.92X10^{-6}$
50	$1.38X10^{-6}$	$1.49X10^{-6}$	$2.00X10^{-6}$	$2.44X10^{-6}$
70	$1.09X10^{-6}$	$1.31X10^{-6}$	$1.74X10^{-6}$	$1.87X10^{-6}$

CHAPTER 4

RESULT AND DISCUSSION I

(STABILIZED FLY ASH-LIME MIXES)

4.1. INTRODUCTION

This chapter delineates the effect of lime on the hydraulic conductivity and leachate characteristics of fly ash. The compaction characteristics of fly ash mixed with different lime content along with the hydraulic conductivity and leachate characteristics of the compacted fly ash specimens were determined after specified curing periods. The effect of lime and curing period on hydration products, and microstructure in the stabilized specimens were studied by various microanalyses such as XRD, and SEM tests. The leachability of different elements is expressed in terms of leachate load ratio. Further the leachate load ratio of different elements in the leachate sample is correlated to the hydration products, pH value and hydraulic conductivity.

4.2. GEOTECHNICAL PROPERTIES OF LIME –FLY ASH MIXES

4.2.1. Water Content- Dry Density Relationship for Lime-Fly Ash Mixes

The light compaction and heavy compaction tests on different fly ash-lime mixes were performed according to IS: 4332(Part III) 1967. The optimum moisture content (OMC) and maximum dry density (MDD) values obtained for different fly ash-lime mixes are presented in Table 4.1. From light compaction test, it was observed that the optimum moisture content varied from 37.92 % to 40.38%, whereas maximum dry density (MDD) ranged from 1.128 to 1.17g/cc. But in case of heavy compaction test it was found that OMC was varied from 30.5 to 36.88 % and MDD from 1.29 to 1.33g/cc.

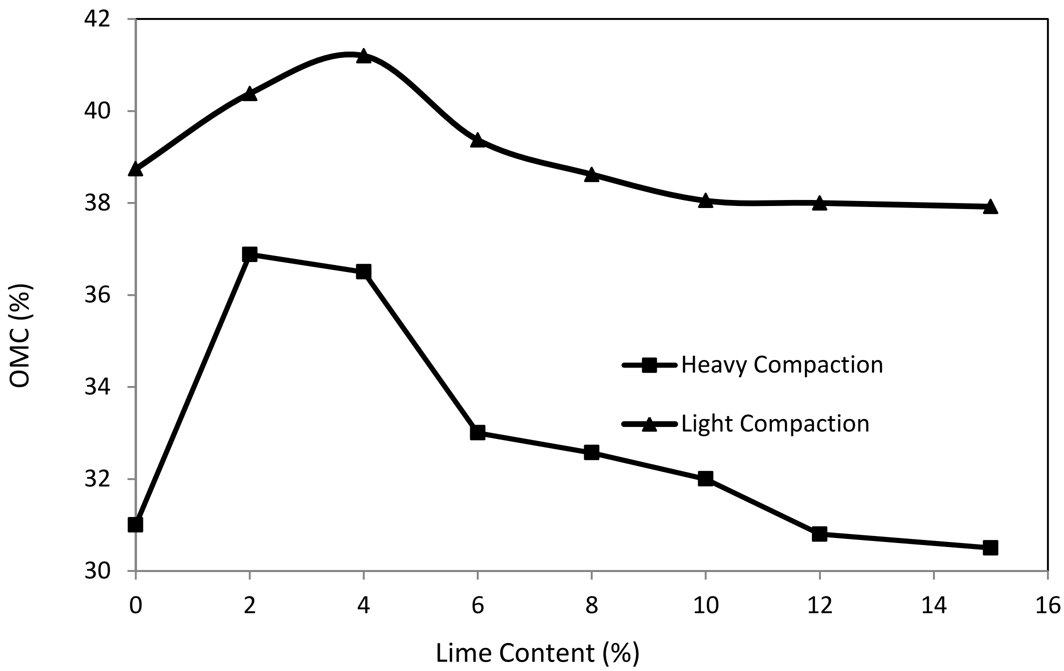


Figure 4.1. Variation of OMC with lime content at light and heavy compaction energies

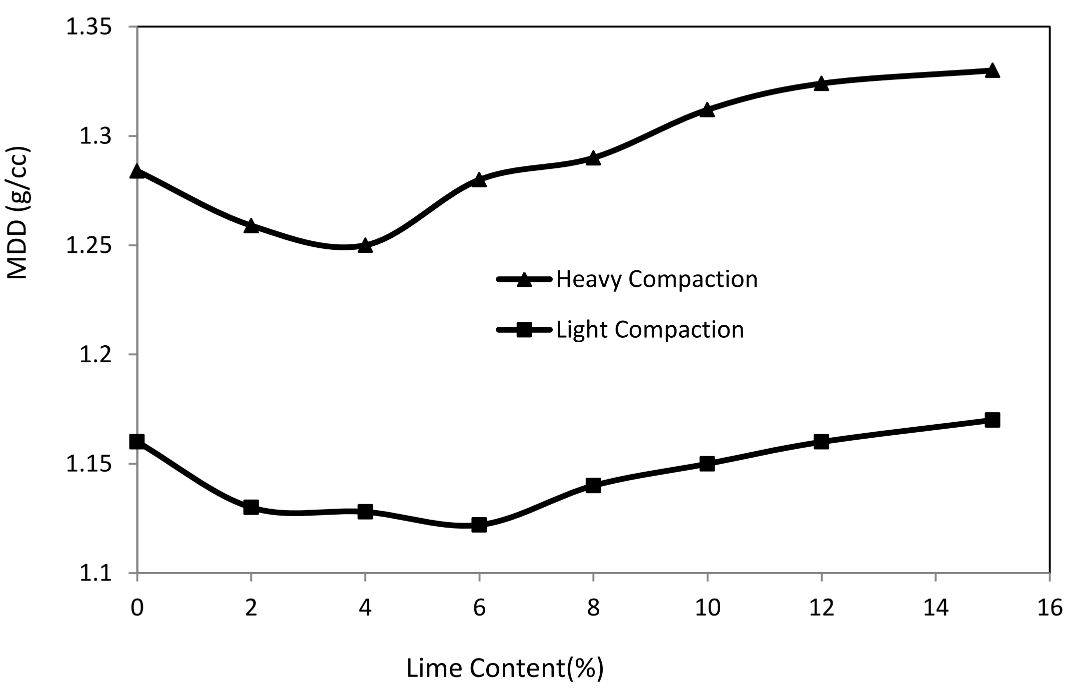


Figure 4.2. Variation of MDD with lime content at light and heavy compaction energies

From Fig. 4.1, it was found that for light compaction test, with increase in lime content the OMC value increases up to 4% and thereafter, it decreases whereas in case of heavy compaction test, the OMC increases up to 2% lime and thereafter, it decreases. Similarly, Fig. 4.2 shows that the MDD in case of light compaction test decreases with increase in lime content up to 4% and thereafter it increases whereas in case of heavy compaction test the same value decreases up to 2% lime addition and thereafter, it increases. Addition of lime to fly ash specimen brings about the colloidal type of reaction in which particles flocculate. As flocculated structure is more resistance to applied force, the particles do not slide to a denser state. However, with further increase in lime the MDD value is found to increase. This may be attributed to higher specific gravity of lime compared to fly ash particles. An increase in OMC value at low lime content is attributed to the flocculated structure of the compacted mass with higher internal void space, which accommodates more moisture. As the formation of cementitious gel products in lime stabilized material is rather a slow phenomenon, it is presumed that the above observed trend is a consequence of colloidal type of reaction rather than the pozzolanic reaction.

4.2.2. Hydraulic Conductivity

Figure 4.3 and Figure 4.4 shows the variation of hydraulic conductivity with lime content for specimens compacted at light as well as heavy compaction energies and cured for different days. It is observed that the hydraulic conductivity values follow a decreasing trend with increase in lime content and it also depends on the compaction effort. Samples having more compaction show less value of permeability. With increase in curing period the permeability of the specimens decreases many fold. This is due to the formation of C-S-H gel which clogs the capillary pore space. However, sample with no lime content showed marginal change in hydraulic conductivity value with curing period. The samples containing higher doses of lime shows significant decrease in hydraulic conductivity value. It was found that at 90 days curing, it reduces about 10 times for samples compacted with light compaction energywhereas in case of heavy compaction, it decreases about 100 times than that of the unstabilized specimen. In a nutshell, permeability depends on lime content, compaction effort and curing period.

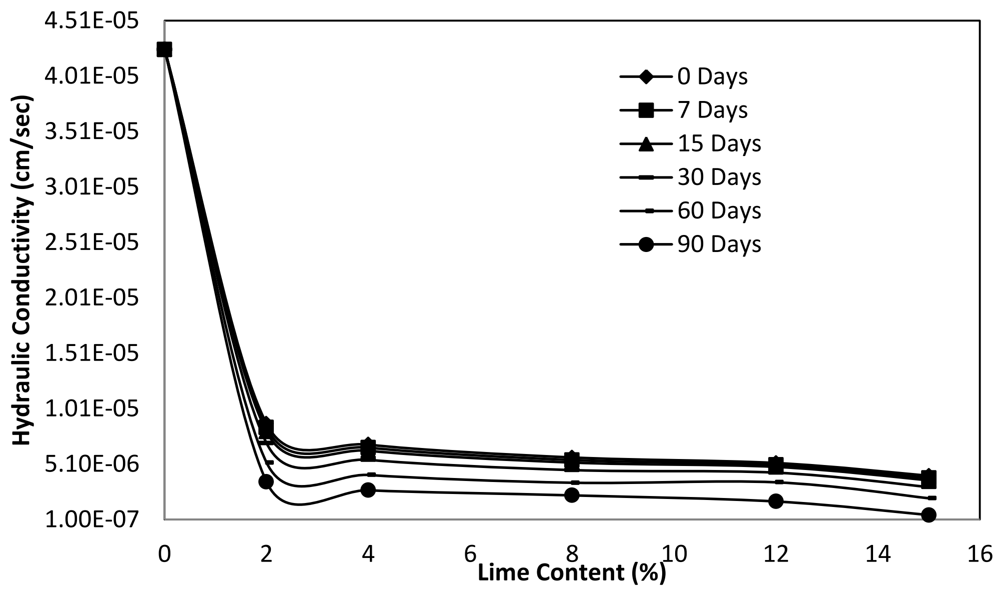


Figure 4.3. Variation of hydraulic conductivity with lime content for light compaction

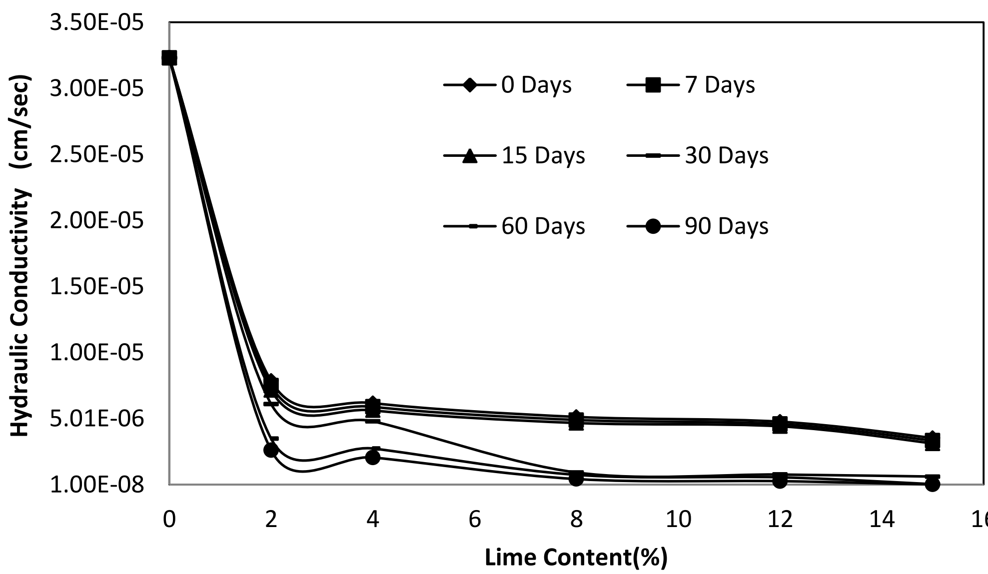


Figure 4.4. Variation of hydraulic conductivity with lime content for heavy compaction

4.2.3. pH Value

Figure 4.5 shows that the pH value of the leachate sample collected from permeability test of compacted fly ash-lime mixes increases with increase in doses of lime. Also it is observed that with increase in curing period i.e. at 90 days the pH value is less than that of 0 days curing period. This is because the pozzolanic reaction in lime treated fly ash continues for a longer period. So at early days of curing the unreacted lime comes out with the leachate. However, with increase in curing period, the lime present in the specimens participate in the pozzolanic reaction, so the amount of lime left in the specimens eventually decreases. Thus, the pH value of the specimens decreases.

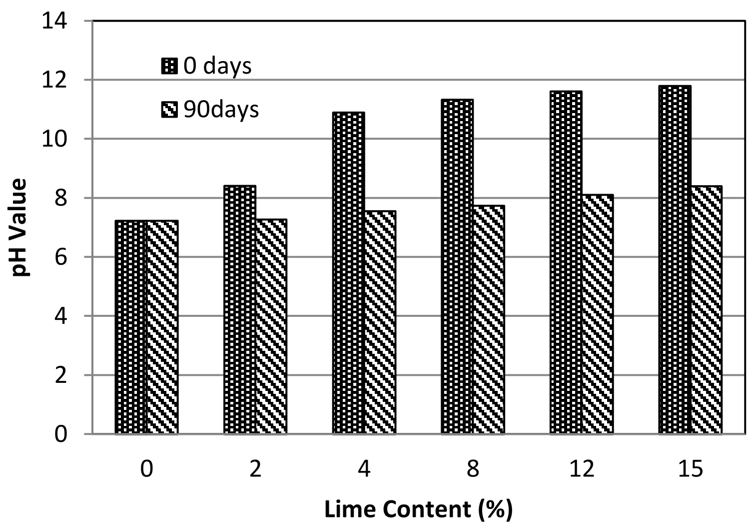


Figure 4.5. Variation of pH with lime content on different days of curing

4.2.4. Leachate Analysis

From the leachate analysis it was observed that at 0 days curing with increase in lime content in the specimens the concentration of Ca increases. However, with increase in curing period the concentration of Ca gradually decreases in all the samples. This is because at early stage of curing the pozzolanic reaction is slow and the unreacted lime leaches out. As the curing period increases, pozzolanic reaction becomes stronger and less amount of lime could leach out. It is also observed that at 90 days curing the concentration of Ca is higher for the specimen containing higher doses of lime. For specimens having low lime content, most of lime added reacts with reactive silica and only a little amount of lime left unreacted which leach out with the percolating water. With increase in lime content, the required amount of lime participates in pozzolanic reaction and rest unreacted lime leaches out with the percolating water. Fig. 4.6 represents the variation of calcium concentration in the leachate sample with lime contents for different curing periods. For a particular lime content the concentration of Ca decreases with higher curing period. This indicates that as the curing period increases the added lime in the fly ash mix takes part continuously in the pozzolanic reaction and is consumed.

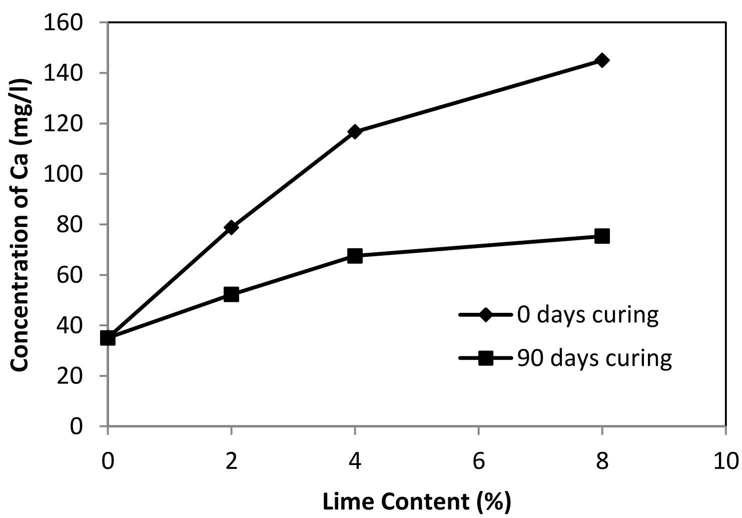


Figure 4.6. Variation in concentration of Ca in the leachate sample with lime content

Table 4.1 Concentration of metals in leachate sample of raw fly ash

Sample ID	Concentration of metals (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
N1	46.409	1.543	23.350	1.699	2.464	1.48	2.172
N2	35.219	0.06	0.057	0.325	1.875	0.159	0.315

N1 denotes the sample prepared from acid digestion of raw fly ash and N2 denotes the extracted leachate sample of raw fly ash (L/S=10).

Table 4.2. Concentration of elements in leachate sample after 0 and 90 days of curing

Elements	Concentration of elements in leachate on 0 day curing(mg/l)				Concentration of elements in leachate on 90days curing(mg/l)			
	FA+0%L	FA+2%L	FA+4%L	FA+8%L	FA+0%L	FA+2%L	FA+4%L	FA+8%L
Cu	0.05	0.046	0.037	0.031	0.05	0.02	0.015	0.01
Zn	0.283	0.258	0.242	0.217	0.282	0.044	0.037	0.021
Ca	35.119	78.721	116.7	145	35.116	52.262	64.548	75.321
Pb	0.256	0.254	0.242	0.239	0.256	0.172	0.139	0.11
Cr	1.252	1.248	1.244	1.243	1.251	0.162	0.153	0.106
Fe	0.05	0.049	0.048	0.047	0.05	0.032	0.025	0.017
Ni	0.151	0.149	0.148	0.144	0.151	0.057	0.043	0.038

Table 4.2 shows the concentration of metals in the leachate collected from permeability mold after 0 days and 90 days curing. From the test it was observed that the concentration of all the metals was less than that of leachate sample of raw fly ash obtained from acid digestion and extraction method (Table 4.1). At 0 days curing the concentration of all the metals expect Ca were approximately same in specimens having different lime contents whereas with increase in curing period the concentration of metals was found to be decreased. This is due to increase in the alkalinity of the medium which is unfavorable for metal precipitation and also due to encapsulation of metals by the hydration products. It is also observed that after 90 days of curing the concentration of all the metals is below the threshold limit of IS-10500 and WHO water quality standard (Table 1.3).

4.2.4.1. Leachate–load ratio

The total amount of a metal in the leachate depends on the hydraulic conductivity of the material and on the concentration of the metal in the leachate. The effect of lime stabilization in mitigating the leachate characteristics of fly ash is studied through the term leachate load ratio which is defined as the ratio of the total metal emanating from an unstabilized specimen per unit time to that of the total metal emanating from a stabilized specimen for same time. The total metal emanating from the specimen is the product of hydraulic conductivity and concentration of the metal under study. When the leachate-load ratio value is greater than 1, it indicates that the total metal coming out of the stabilized specimen per day is less than the total metal emanating from unstabilized specimen. Table 4.3 shows that the leachate load ratio for all the elements are greater than 1. Therefore, the total metal coming out of the stabilized specimen is less than the total metal emanating from unstabilized specimen. It also shows that with increase in lime content the leachate-load ratio of each metal follows an increasing trend.

Table 4.3. Leachate load ratio values for different metals in samples cured for 90 days

Mix Proportion	Leachate load ratio of of metals						
	Cu	Zn	Ca	Pb	Cr	Fe	Ni
FA+0%L	1	1	1	1	1	1	1
FA+2%L	7.66	19.64	2.06	19.98	23.67	4.79	8.12
FA+4%L	13.01	29.76	2.12	31.49	31.93	7.81	13.71
FA+8%L	23.46	63.02	2.18	47.82	55.38	13.80	18.62

4.2.5. Hydration products and Morphology

The hydration products, morphology and microstructure formed during hydration process were studied using XRD and SEM analysis. The XRD patterns of fly ash specimens containing different doses of lime on 90 days curing are shown in Fig. 4.4. A series of compounds such as quartz (Q), calcite (C), hematite, ettringite (E), and calcium silicate hydrate (B), calcium aluminiumate hydrate (A) are found in hydrated specimens. As the curing period increases, (Fig.4.5) hydration products or phases are intensified and the peaks of calcite diminishes. The diminished intensity of calcite peaks with an increased curing time is an indication of participation of lime in hydration process and formation of more amount of C-S-H gel.

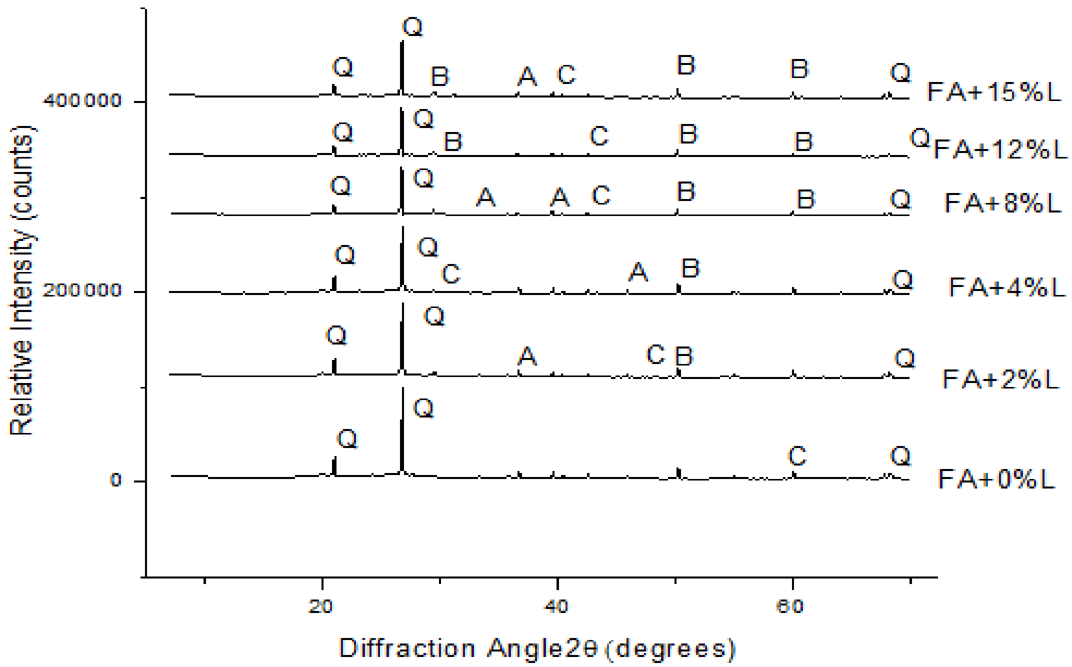


Figure 4.4 XRD analyses of specimens containing different doses of lime on 90 days curing

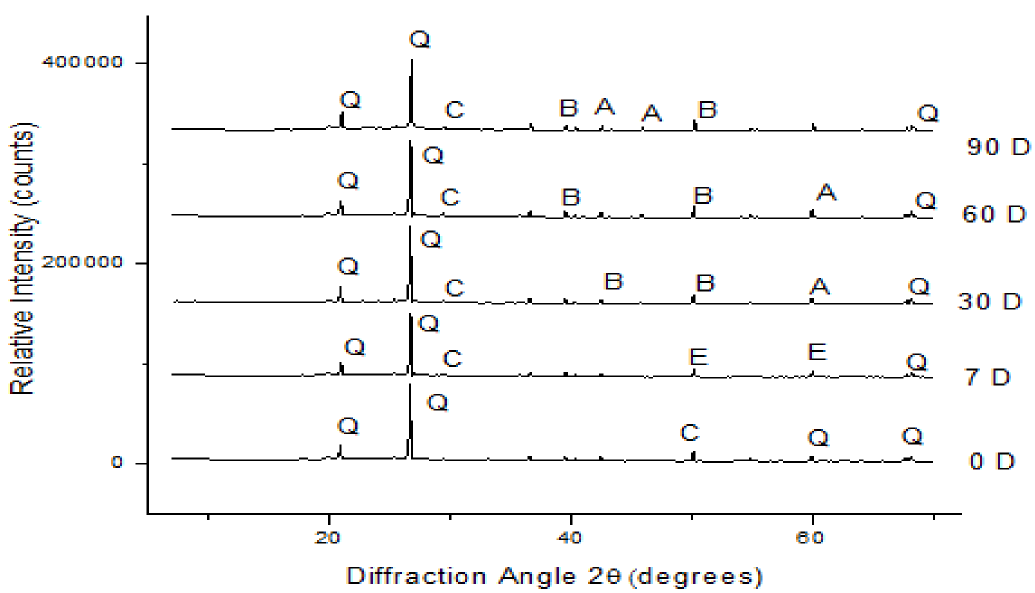


Figure 4.5 XRD analysis of FA+4%L specimen on different days of curing

The microstructure and hydration products of specimens cured for different periods are studied using scanning electron microscope. Figure 4.8 and 4.9 shows the hydration products in specimens containing 4% and 15% of lime respectively and cured for 90days. Abundance of needle-like structures of ettringite is found in the specimen cured for 7 days (Figure 4.7). Usually needle like crystals appeared during the early period of hydration. As curing proceeds the needle shaped crystals are seen wrapped with gel like substances of calcium silicate hydrate. A further increase in the curing period resulted in formation more amount of C-S-H gel (Fig. 4.8 and 4.9). This results in reduction of capillary voids and decrease in hydraulic conductivity value. The SEM analysis shows the compounds that are identified earlier from XRD analysis.

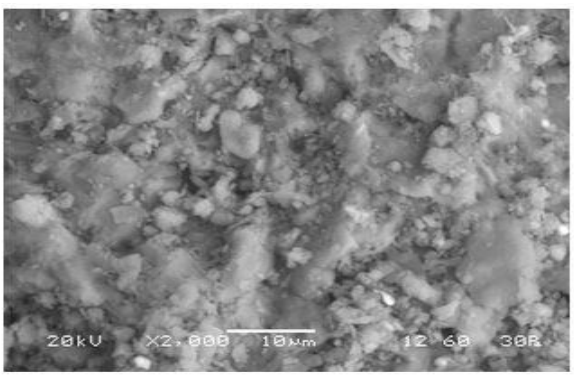


Figure 4.6. SEM image of FA+4%L specimen on 0 day curing

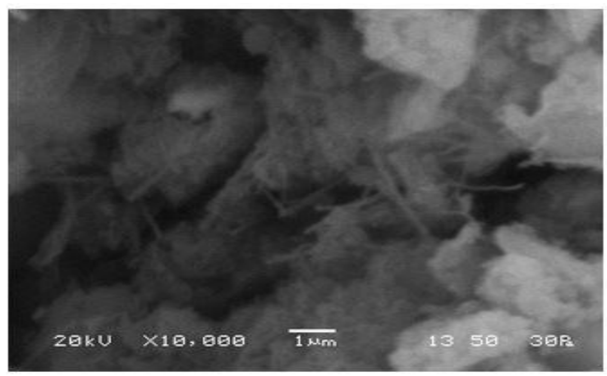


Figure 4.7. SEM image of FA+4%L specimen on 7 days curing

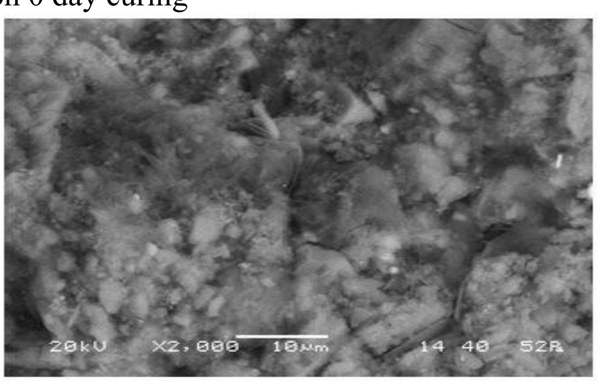


Figure 4.8. SEM image of FA+4%L specimen on 90 days curing

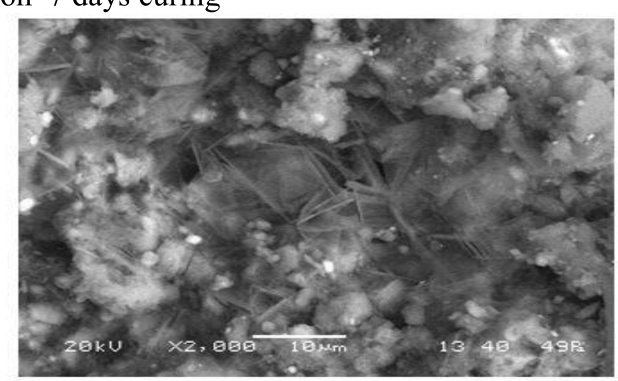


Figure 4.9. SEM image of FA+15%L specimen on 90 days curing

CHAPTER 5

RESULT AND DISCUSSION-II
(FLY ASH BED TREATED WITH LIME COLUMN)

5.1. INTRODUCTION

Lime columns are often used to stabilize soft saturated cohesive soil deposits. It is one of the promising and cost effective in-situ stabilization method practised for cohesive soils. However a limited literature is avalable on stabilization of fly ash bed using this technique. The present work used lime column method to reduce the hydraulic conductivity and mitigate the leachate characteristics of sedimented and compacted fly ash deposits. All the results of the above investigations and their corresponding analyses have been presented in the following sections.

5.2. SEDIMENT POND ASH BED TREATED WITH LIME COLUMN

5.2.1. pH test

Figure 5.1 and 5.2 represent the pH test results of the samples collected from different radial distances and depths of the test tank after 90 days , 180 and 365 days curing respectively. It is observed that pH value follows a decreasing trend with an increase in radial distance and follows an increasing trend with increase in depth from the top surface of the pond ash deposit. This is due to migration of lime to the periphery and bottom of the tank. As there is much concentration of lime at the location near to the lime column, so pH value is higher for the samples collected adjacent to the lime column. Similarly an increasing trend of pH value with increase in depth from the surface of the tank is due to migration of lime towards downward direction. Moreover, it is also observed that the pH value increases with curing period (upto 180 days). This indicates that the migration of lime continues even upto 180 days, and the amount of lime migrated is higher than the amount of lime consumed in pozzolanic reaction. This leads to a gradual increase in the pH value. However, beyond 180 days of curing, the pH value is found to be reduced due to participation of more lime in pozzolanic reaction. Further, the migration of lime from lime column towards the peripheral region reduces with time as the hydration products clogs the capilarry voids. The pH value of the pore water always remains above 7.0, indicating an alkaline environment. The alkaline medium of the pore fluid reduces the solubility of metal ions and thus help in controlling the migration of metals from the sedimented fly ash bed.

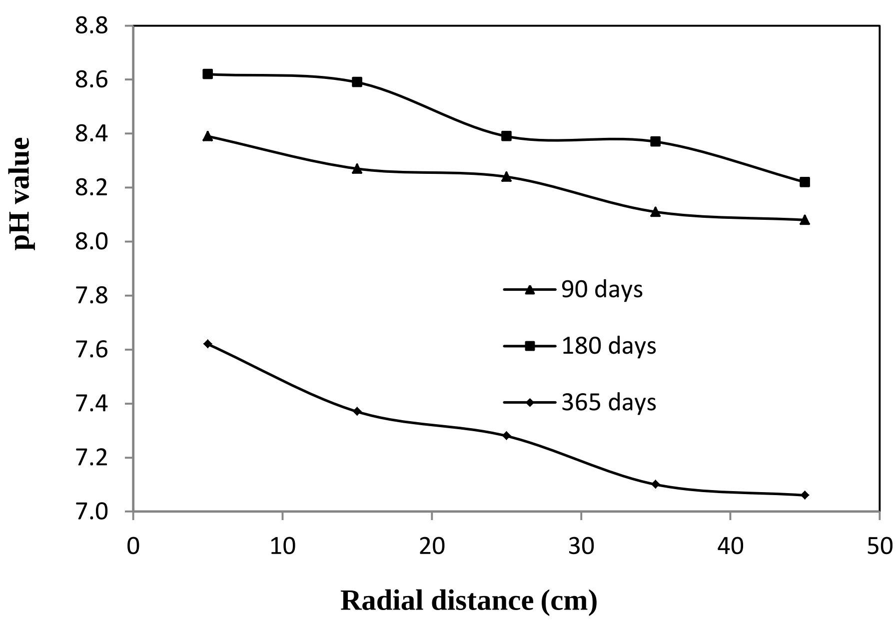


Figure 5.1. Variation of pH value with radial distance

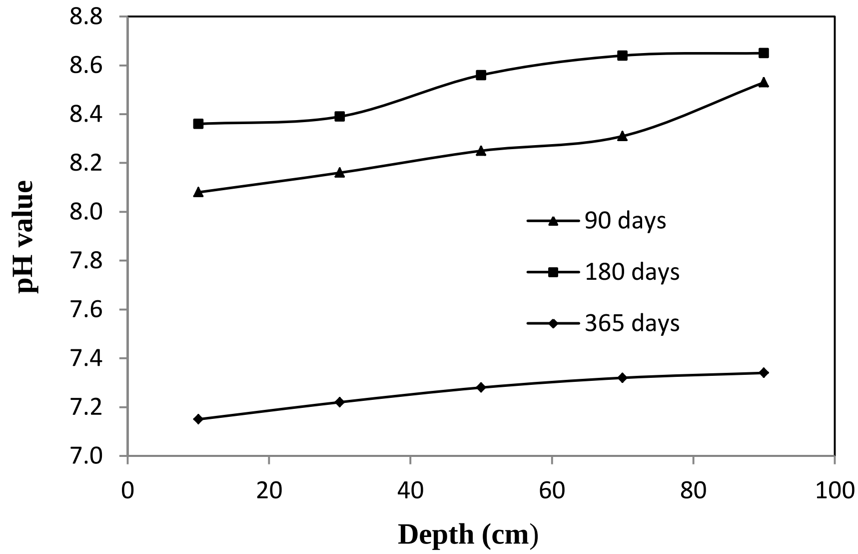


Figure 5.2. Variation of pH value with depth

5.3.2. Hydraulic Conductivity

Figure 5.3, 5.4 and 5.5 represent the hydraulic conductivity values of pond ash specimens collected after 90, 180 and 365 days of curing period respectively. From the test results, it is found that the hydraulic conductivity follows a decreasing trend with increase in depth from the top surface of the fly ash bed and also a reduced value is obtained in the samples collected adjacent to the lime column compared to the remote areas. As the lime migrates from the central lime column toward the periphery it gets distributed over an larger area and thus the concentration get reduced. As there is much concentration of lime at the location near to the lime column, so hydraulic conductivity is lesser for the samples collected adjacent to the column whereas the hydraulic conductivity is more for the samples collected at a remote area from the lime column.

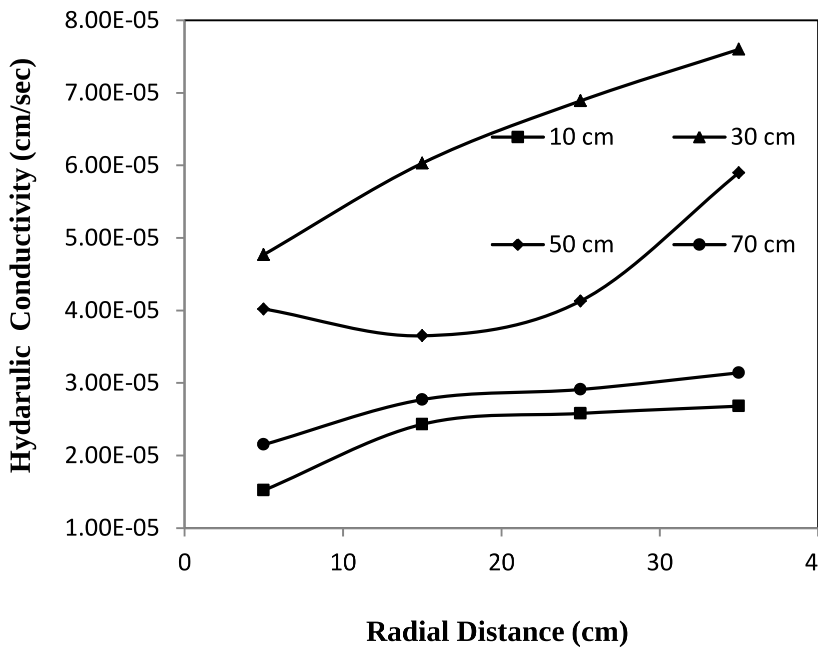


Figure 5.3. Variation of hydraulic conductivity with radial distance on 90 days curing

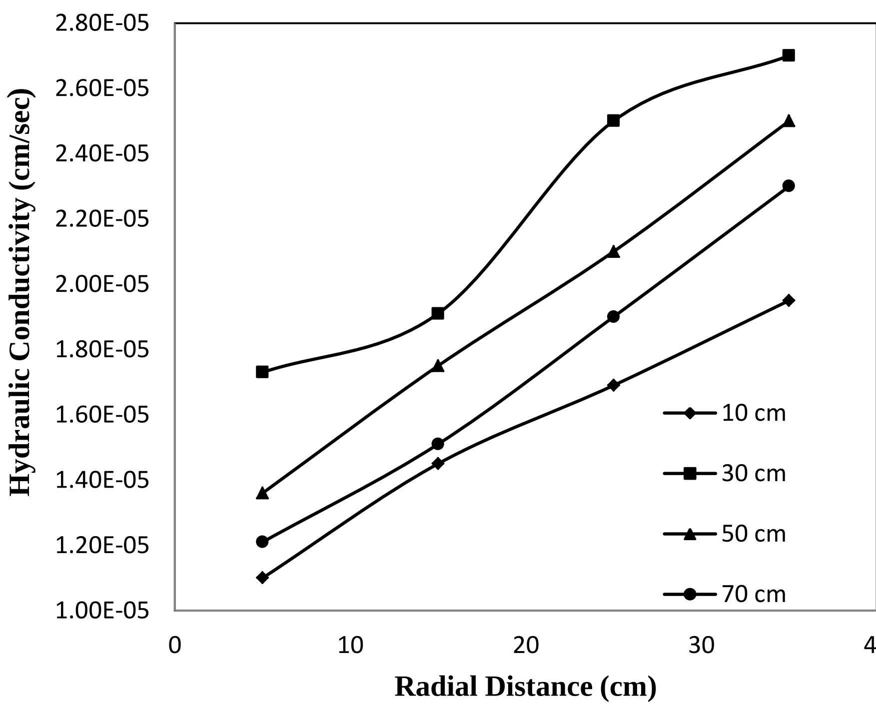


Figure 5.4. Variation of hydraulic conductivity with radial distance on 180 days curing

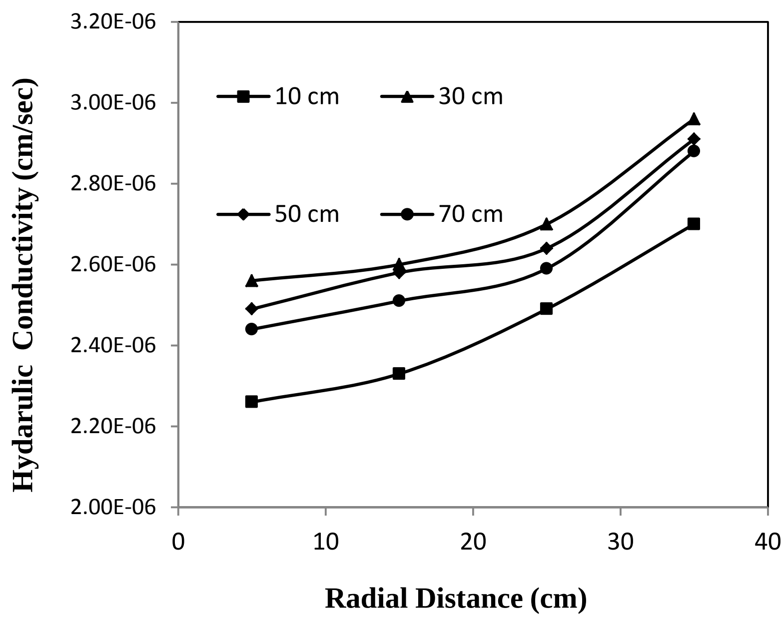


Figure 5.5. Variation of hydraulic conductivity with radial distance on 365 days curing

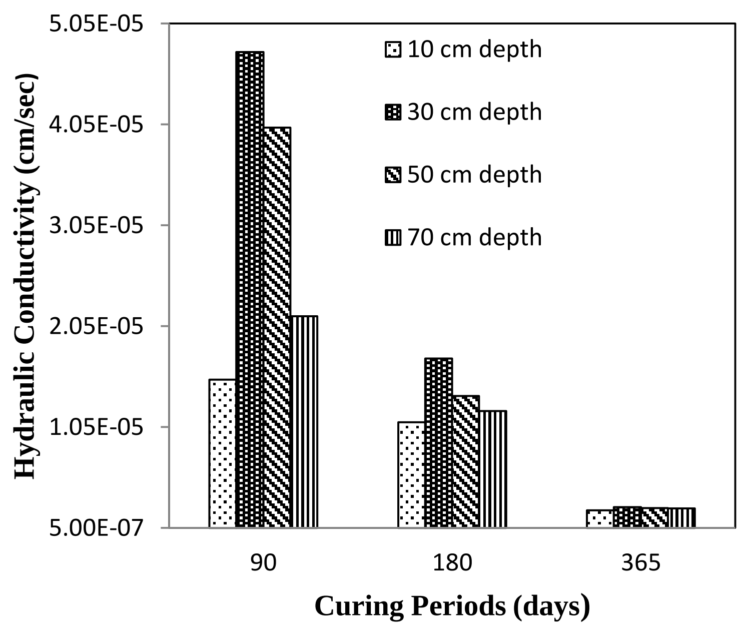


Figure 5.6. Variation of hydraulic conductivity with curing periods at different depths

The reduced value of hydraulic conductivity is due to the formation of hydration products like C-S-H , C-A-H, and C-A-S-H gels which causes a reduction of void space and the interconnectivity of pore channel gets reduced. The test results show that hydraulic conductivity at depth 10cm is less than depth 90. This indicates the presence of finer size particles on the top layer and coarser size at the bottom layer. Another possible reason for decrease in permeability on the top layer may be due to the evaporation of lime added water from the surface of the pond ash deposit and participation of efflorescent lime in the hydration reaction. It is also observed from Fig. 5.6 that as the curing period increases, significant reduction in hydraulic conductivity occurs in all the layers of sediment pond ash deposit. This indicates that the hydration reaction becomes even more stronger with a higher curing period, which causes the generation of more amount of hydration products and hence reduction in hydraulic conductivity.

5.3.3. Leachate Analysis

The leachate analysis results of sample collected on 90 , 180 days and 365 days curing are given in Table 5.1, 5.2 and 5.3 respectively. It shows that concentration of elements in the leachte sample collected from the test tank is much lower than the leachte sample extracted from raw fly ash (Table 4.1). It also shows that at early period of curing the concentration of Ca is more whereas in the longer curing period, i.e at 365 days, the concentration of Ca gradually reduces. This is because during initial stage of the curing period the pozzolanic reaction is slow and the unreacted lime leached out very easily. However, at the longer curing period the concentration of calcium decreases due to participation of lime in pozzolanic reaction. It is also observed that the concentration of Ca in sample follows an increasing trend in the sample collected at same radial distances but varying depth in the order of S1<S2<S3<S4<S5 due to migration of lime in downward direction, whereas the concentration of Ca in samples follows a decreasing trend in the samples collected at the same depth but different radial distance in the order of S6>S7>S3>S8>S9 due to lesser migration of lime at greater radial distance from the lime column. It is also observed from the results that the concentration of major and trace elements in the leachate sample collected adjacent to the lime column is lesser than that of the sample collected at the periphery of the test tank. This is due to the migration of lime from the lime column towards the periphery resulting in higher pH value near the lime column and lower pH value at a remote area from lime column which provides an unfavorable alkaline medium for metal precipitation. Similarly, as with increase in depth from the top surface of the pond ash deposit , the concentration of the element decreases due to downward movement of the lime from the lime column.

Table 5.1. Concentration of metals in leachate on 90 days curing

Samples	Concentration of metals (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	78.211	0.059	0.324	0.251	1.369	0.126	0.259
S2	93.102	0.052	0.314	0.183	1.354	0.118	0.253
S3	93.699	0.051	0.296	0.181	1.132	0.108	0.145
S4	97.390	0.049	0.173	0.175	1.203	0.097	0.068
S5	98.235	0.024	0.107	0.151	1.047	0.052	0.065
S6	96.805	0.047	0.049	0.164	1.423	0.1	0.050
S7	96.463	0.050	0.112	0.169	1.493	0.104	0.099
S8	90.467	0.054	0.180	0.210	1.529	0.113	0.165
S9	89.446	0.056	0.332	0.223	1.587	0.114	0.236

Note: S1, S2, S3, S4, S5 are the leachate samples collected from same radial distance that is at 25cm but with varying depth of 10cm, 30cm, 50cm, 70 cm and 90cm respectively, whereas S6, S7, S8, S9 are the samples collected from same depth ,that is 50cm but at different radial distances of 5cm, 15cm, 35cm and 45cm respectively.

Table 5.2. Concentration of metals in leachate on 180 days curing

Samples	Concentration of metals in leachate (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	71.481	0.028	0.052	0.194	1.003	0.124	0.115
S2	71.790	0.025	0.029	0.172	0.940	0.044	0.095
S3	72.365	0.024	0.026	0.139	0.811	0.035	0.081
S4	76.628	0.021	0.016	0.083	0.784	0.028	0.071
S5	77.275	0.019	0.013	0.011	0.692	0.022	0.036
S6	75.426	0.013	0.011	0.112	0.527	0.010	0.044
S7	72.795	0.023	0.012	0.136	0.537	0.024	0.073
S8	69.925	0.027	0.029	0.163	1.168	0.052	0.113
S9	68.231	0.030	0.036	0.204	1.271	0.071	0.174

Table 5.3. Concentration of metals in leachate on 365 days

Samples	Concentration of metals in leachate (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	47.995	0.021	0.026	ND	0.587	0.041	ND
S2	48.267	0.018	0.025	ND	0.579	0.039	ND
S3	48.581	0.016	0.017	ND	0.571	0.033	ND
S4	48.897	0.014	0.014	ND	0.564	0.024	ND
S5	49.686	0.011	0.012	ND	0.491	0.006	ND
S6	49.183	0.010	0.007	ND	0.427	0.009	ND
S7	48.886	0.013	0.01	ND	0.521	0.012	ND
S8	48.232	0.017	0.017	ND	0.601	0.48	ND
S9	48.02	0.028	0.032	ND	0.632	0.051	ND

Moreover, it is observed with increase in curing period, the concentration of elements in the leachate decreases. This is due to the formation of hydration product such as C-S-H gel which encapsulates the elements and prevents leaching. So this confirms that addition of lime plays a pivotal role in reducing the concentration of elements and with higher curing period the concentration of element reduces even more. The concentration of all the elements was found to be less than threshold limit of WHO and IS-10500 (Table 1.3) water quality standard.

5.4. COMPACTED FLY ASH BED TREATED WITH LIME COLUMN

5.3.1 pH test

Figure 5.7 and 5.8 represent the pH test results of the samples collected from different depths and radial distances of the test tank after 90, 180 and 365 days of curing. It is observed that the pH value is more at the locations adjacent to the lime column and less in the sample collected at a remote area from the lime column. The value follows an increasing trend with increase in depth from the top surface of the pond ash deposit. This is due to migration of lime to the surrounding and downward direction of the tank. As there is much concentration of lime at the location near to the lime column, the pH value is more and as there is less concentration of lime at the remote area from the lime column the same value is less. Moreover, it is also observed that the pH value increases with increase in curing period (up to 180 days). This indicates that the amount of lime migrated is higher than the amount of lime consumed in pozzolanic reaction. This leads to a gradual increase in the pH value. However, with further curing that is after 180 days the pH value decreases due to participation of lime in pozzolanic reaction. The pH value of the pore fluid of sedimented and compacted ash beds are found to be almost equal for comparable conditions that is at same location and same curing period. This shows that the degree of compaction has not much influence on the migration of lime from the central column towards the peripheral region.

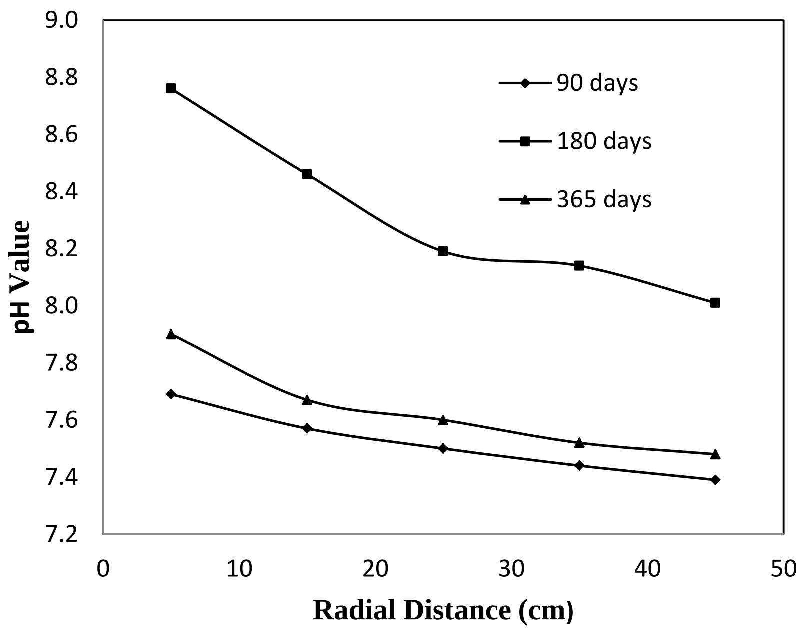


Figure 5.7. Variation of pH value with radial distance

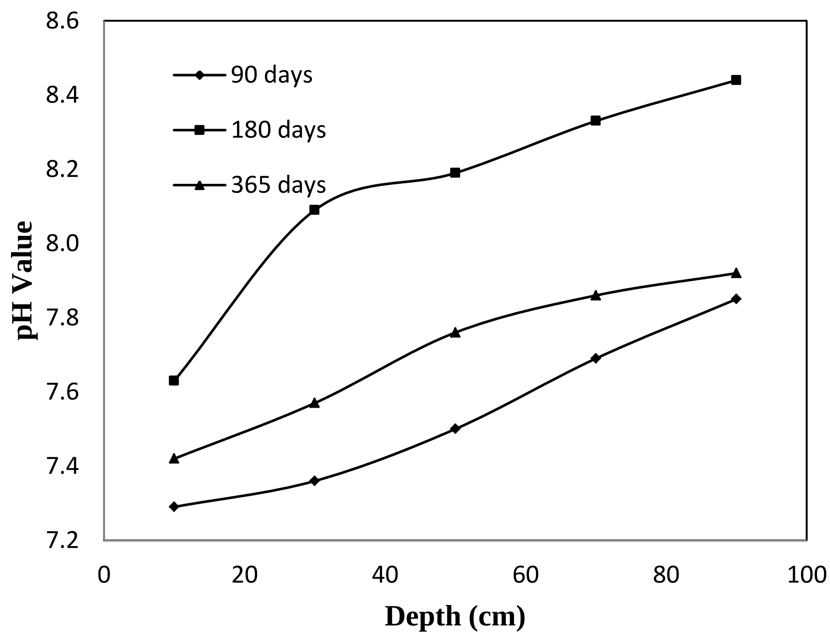


Figure 5.8. Variation of pH value with depth

5.3.2 Hydraulic Conductivity

The hydraulic conductivity fly ash specimens were determined after 90, 180 and 365 days curing period and the results are presented in Fig. 5.9, 5.10 and 5.11 respectively. It is observed that the hydraulic conductivity follows a decreasing trend as with increase in depth and also a reduced value is obtained in the samples collected adjacent to the lime column.This is due to the uneven concentration of lime in different parts of the compacted bed. As there is much concentration of lime at the locations near to the lime column, so hydraulic conductivity is lesser for the samples collected adjacent to the column whereas the hydraulic conductivity is more for the samples collected at a remote area from the lime column. The reduced value of hydraulic conductivity is obtained due to the participation of lime in hydration reaction and formation of hydration products like C-S-H, C-A-S and C-A-S-H gels which cause a reduction of void space and interconnectivity of pore channel. In addition, it is also observed from Fig. 5.12 that as the curing period increases, a significant reduction in hydraulic conductivity occurs in all the locations of compacted fly ash bed. This reduction in the hydraulic conductivity is more pronounced in locations near to the lime column than farther points. This indicates that the hydration reaction becomes even more stronger with a higher curing period, which causes the generation of more amount of hydration products and hence reduction in hydraulic conductivity. The hydraulic conductivity of untreated compacted fly ash was 4.25×10^{-5} cm/sec which reduced to 1.09×10^{-6} cm/sec after a curing period of 365 days and at a radial distace of 5cm from lime column and depth of 70cm. This is of a reduction of about 22 times. This reduction in hydraulic conductivity of the fly ash bed helps in mitigating the migration of heavy and trace elements from the bed towards the surrounding areas.

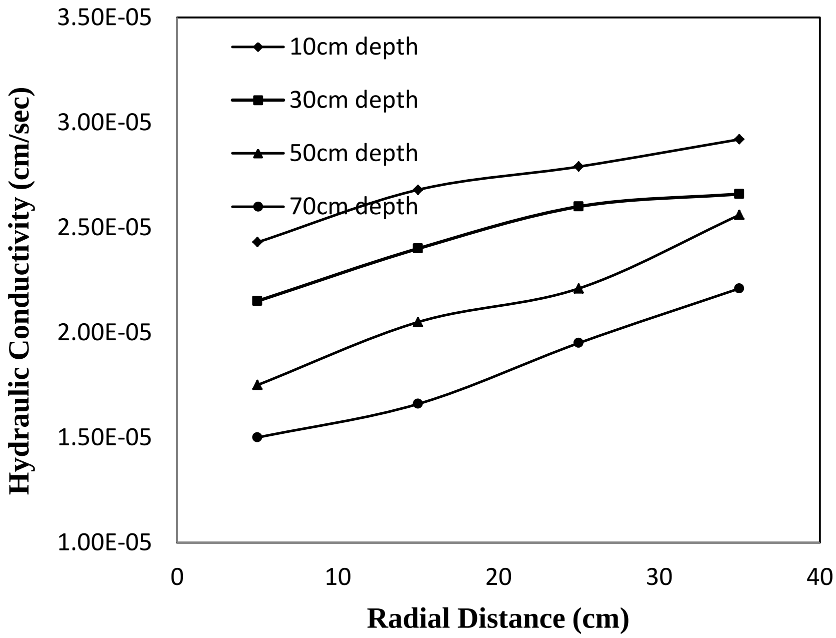


Figure 5.9. Variation of hydraulic conductivity with radial distance on 90 days curing

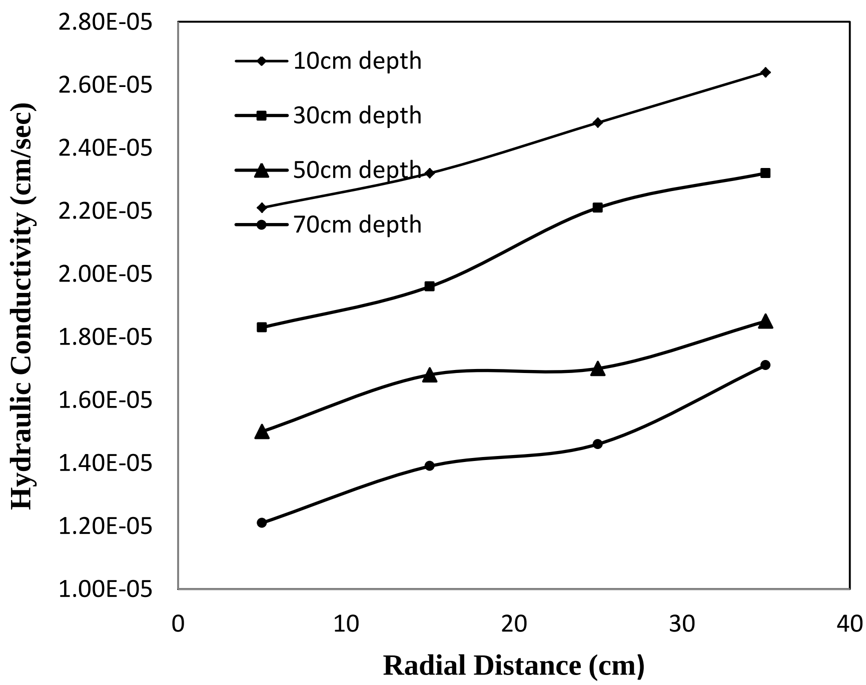


Figure 5.10. Variation of hydraulic conductivity with radial distance on 180 days curing

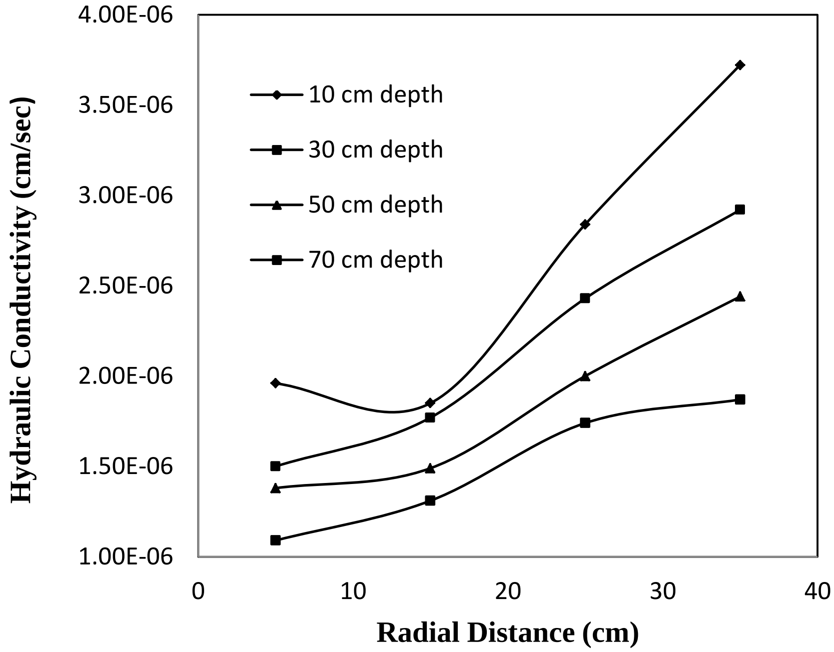


Figure 5.11. Variation of hydraulic conductivity with radial distance on 365 days curing

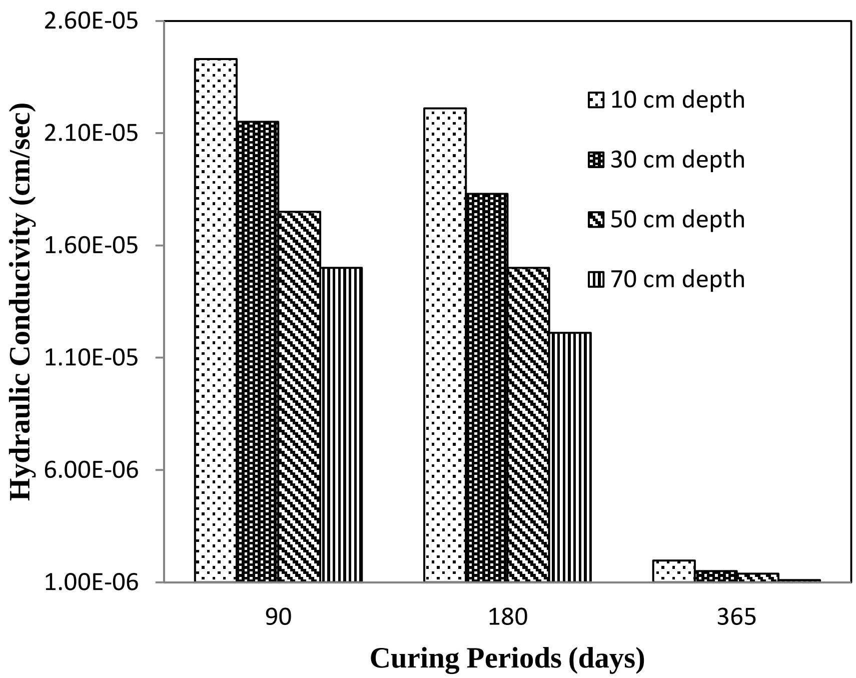


Figure 5.12. Variation of hydraulic conductivity with curing periods at different depths

5.3.3. Leachate Analysis

The leachate analysis results of sample collected on 90, 180 days and 365 days curing are given in Table 5.4, 5.5 and 5.6 respectively. It shows that concentration of all elements in the leachate samples collected from the test tank are much lower than that extracted from raw fly ash (Table 4.1). It also shows that at early period of curing the concentration of Ca in the leachate sample collected from all the locations of the tank is more than that in the virgin fly ash. The concentration of Ca in the leachate sample continues to increase up to a curing period of 180 days thereafter the same follows a decreasing trend. During initial period there is profuse migration of lime from the lime column towards the surrounding. As curing period increases the migrated lime takes part in pozzolanic reaction producing the C-S-H gel. This gel blocks the capillary pore space of thee ash bed thus prohibiting further migration of lime which results in a decrease in the concentration of Ca in the leachate sample with longer curing period. Further, it is observed that the concentration of Ca in sample follows an increasing trend with increase in depth whereas the same follows a decreasing trend with increase in radial distance. This is due to the migration of lime to the surrounding and distribution of migrated lime over a wider area. It is also observed from the results that the concentration of other major and trace elements in the leachate sample collected adjacent to the lime column is lesser than that of the sample collected at the periphery of the test tank. This is due to the presence of higher concentration of lime at the location adjacent to the lime column which results in higher pH value near the lime column and lower at a remote area from lime column thus, providing an unfavorable alkaline medium for metal precipitation. In addition to this, the higher concentration of lime results in the formation of more amount of C-S-H gel which encapsulates the metal ions and thus, prevents leaching of elements.

Table 5.4. Concentration of metals in leachate on 90 days curing

Samples	Concentration of Metals (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	91.339	0.049	0.025	0.190	ND	0.124	0.259
S2	91.520	0.044	0.024	0.170	ND	0.118	0.253
S3	91.693	0.038	0.016	0.140	ND	0.108	0.145
S4	91.886	0.034	0.011	0.081	ND	0.097	0.068
S5	92.700	0.026	0.013	0.012	ND	0.052	0.065
S6	91.762	0.019	0.008	0.113	ND	0.1	0.044
S7	91.717	0.027	0.02	0.134	ND	0.104	0.099
S8	89.594	0.041	0.017	0.165	ND	0.113	0.165
S9	89.125	0.047	0.032	0.207	ND	0.114	0.174

Table 5.5. Concentration of metals in leachate on 180 days curing

Samples	Concentration of Metals (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	87.995	0.029	0.017	0.094	ND	0.044	ND
S2	88.02	0.028	0.015	0.077	ND	0.043	ND
S3	88.686	0.025	0.008	0.074	ND	0.037	ND
S4	88.581	0.021	0.006	ND	ND	0.029	ND
S5	88.886	0.014	ND	ND	ND	0.01	ND
S6	89.183	0.011	ND	ND	ND	0.02	ND
S7	88.897	0.023	0.001	ND	ND	0.033	ND
S8	88.267	0.032	0.014	ND	ND	0.059	ND
S9	88.232	0.034	0.017	0.073	ND	0.08	ND

Table 5.6. Concentration of metals in leachate on 365 days curing

Samples	Concentration of Metals (mg/l)						
	Ca	Cu	Fe	Pb	Cr	Ni	Zn
S1	41.535	0.007	ND	ND	ND	0.027	ND
S2	40.270	0.005	ND	ND	ND	0.022	ND
S3	39.767	0.004	ND	ND	ND	0.019	ND
S4	38.172	0.003	ND	ND	ND	0.011	ND
S5	32.688	0.002	ND	ND	ND	ND	ND
S6	35.113	0.001	ND	ND	ND	0.015	ND
S7	38.155	0.002	ND	ND	ND	0.018	ND
S8	39.012	0.005	ND	ND	ND	0.037	ND
S9	40.724	0.006	ND	ND	ND	0.05	ND

Note: ND denotes these elements are below detection level.

Moreover, it is observed with increase in curing period, the concentration of elements in the leachate decreases. This is due to the formation of hydration products such as C-S-H, C-A-S and C-A-S-H gels which encapsulates the elements and prevents leaching. So this confirms that addition of lime plays a pivotal role in reducing the concentration of elements and with higher curing period the concentration of element reduces even more. The concentration of all the elements was found to be less than threshold limit of WHO and IS-10500 water quality standard (Table 1.5). Particularly the concentration of metals like Fe, Pb, Cr, and Zn are found to be below detection level.

5.5. HYDRAULIC CONDUCTIVITY AND LEACHATE LOAD RATIO OF SEDIMENT AND COMPACTED FLY ASH BED

5.4.1. Hydraulic Conductivity

It is observed from Figure 5.7 that in all the layers the hydraulic conductivity value of the specimens collected from compacted fly ash bed is smaller than that of sediment pond ash deposits. This is due to the presence of more dense layer in case of compacted fly ash bed than that of sedimented pond ash bed which leads to the reduction of voids and hence, reduction in hydraulic conductivity

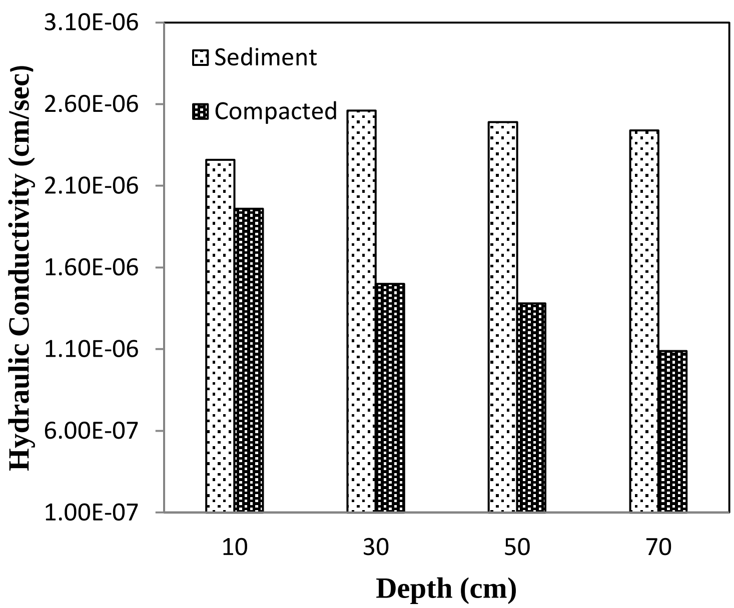


Figure 5.7 Variation of hydraulic conductivity with depth in the specimens collected from 5cm radial distance in the ash beds on 365 days curing

5.4.1. Leachate Load Ratio

Leachate-load ratio of an element indicates the total amount of metal coming out of the unstabilized specimen to that of a stabilized specimen at comparable conditions. It primarily depends upon the concentration of element in the leachate sample as well as the hydraulic conductivity of the sample. As the stabilization process continues the hydraulic conductivity of the specimen decreases and the element gets encapsulated in the hydration products formed during pozzolanic reaction and hence, the leachate-load ratio increases. A higher value of leachate-load ratio indicates lesser migration of an element. The leachate-load ratio of different elements after different curing periods has been evaluated. Figure 5.7 shows a typical values of leachate-load ratio of Cu at locations S1, S2, S3 and S4 for sediment and compacted ash beds after curing period of 365 days. In general, the leachate-load ratio obtained from compacted bed is higher than the sedimented bed at comparable conditions (same location and curing period). This is due to the lower hydraulic conductivity of compacted ash bed than the sedimented one. In addition to this, the lower value of concentration of this element in case of compacted ash bed on 365 days curing (Table 5.6) compared to sedimented bed (Table 5.3) also confirms the higher encapsulation of elements by hydration products.

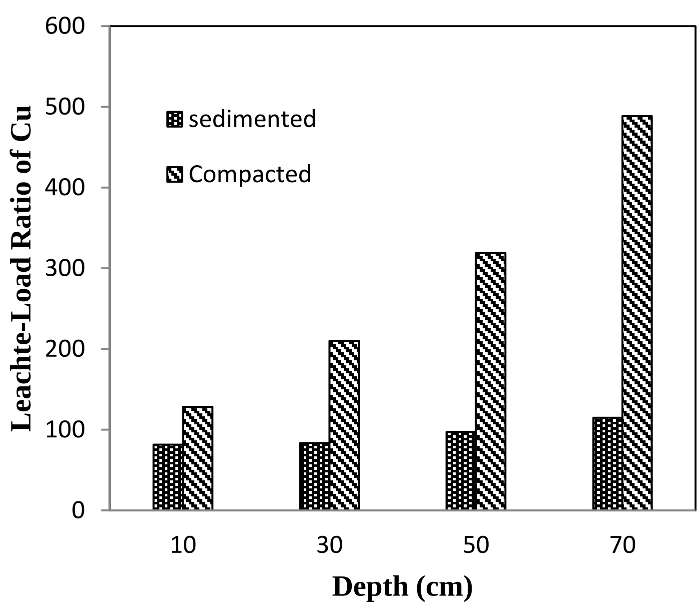


Figure 5.8 Variation of leachate load ratio of Cu with depth in the specimens collected at 25cm radial distance in the ash beds on 365 days curing

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. SUMMARY

Disposal of fly ash is a major issue faced by the coal based thermal power plants. It requires a huge disposal area and creates environmental problem like leaching and dusting. Stabilization of fly ash by chemical additives is one of the promising methods to transform the waste material into a safe construction material. The primary objective of this study is to reduce the concentration of metals in the leachate emanating from the fly ash bed and also to prevent the leachate effluents from contaminating the ground water. Based on this, the scope of the present study is defined and the same has been summarized in Chapter 2. The details of procedure adopted for sample preparation and details of experimental studies undertaken are presented in Chapter 3. Chapter 4 delineates the effect of lime on the hydraulic conductivity and leachate characteristics of fly ash while Chapter 5 highlights the efficacy of lime column in reducing the hydraulic conductivity and leachate characteristics of sediment and compacted fly ash bed. In the present chapter the conclusions drawn from the test results are presented.

6.2. CONCLUSIONS

Based on test results the following conclusions can be drawn.

1. The concentration of metals in leachate majorly depends on two factors, pH and hydraulic conductivity. With increase in lime content, compaction effort, and curing period, the hydraulic conductivity value was found to be decreased. At higher curing

period the reduction in hydraulic conductivity is due to the formation of C-S-H, C-A-H and C-A-S-H gels which clogs the pores and decreases the capillary voids.

2. The pH value of the leachate sample collected after permeability test increases with increase in doses of lime. With increase in curing period the pH value of leachate collected from the permeability samples decreases due to participation of lime in pozzolanic reaction
3. From leachate analysis it was found that at higher curing period with increase in lime content the concentration of metals in the leachate decreases. The leachate load ratio values of all the metals are greater than 1.Therefore, the total metal coming out from the stabilized specimen is less than the total metal coming out from the unstabilized specimen. The reduction in concentration of all the metals is due to presence of alkaline medium which is unfavorable for metal precipitation and also due to encapsulation of metals by the hydration products.
4. It is also observed that the concentration of other metals is below the threshold limit of IS-10500 and WHO water quality standard.
5. From XRD analysis it is found that a series of compounds such as quartz, calcite, hematite, calcium silicate hydrate, calcium aluminium silicate hydrate and calcium aluminium silicate hydrate are formed in hydrated specimens. As the curing period increases, hydration products or phases are intensified and the peaks of calcite diminishes. The diminished intensity of calcite peaks with an increased curing time in the specimen is an indication of participation of lime in hydration process and formation of more amount of C-S-H gel.

6. SEM analysis shows that Abundance of needle-like structures are found in the specimen at initial stage of curing. However, at later stage of curing, common fibrous type of irregular grains forming a reticular network of calcium-silicate-hydrate gel is found. The presence of hydration products result in reduction of hydraulic conductivity value.
7. Thus, lime treatment is an effective means of reducing the hydraulic conductivity and concentration of metals in the leachate emanating from compacted fly ash specimens.

Samples were collected from different depths as well as radial distances of sediment and compacted fly ash bed and subjected to different tests such as pH, leachate analysis and hydraulic conductivity. Based on the experimental findings, the following conclusions are drawn.

1. The pH value of the samples was found to be decreased radially and increased vertically due to migration of lime and thus provides an alkaline medium in reducing the solubility of the toxic metals.
2. With higher curing period the hydraulic conductivity value was found to be decreased vertically due to migration of lime and formation of C-S-H gel which clogs the pores and decreases the capillary voids.
3. From the leachate analysis, it is observed that the concentration of Ca increases at the early period of stabilization due to the migration of lime from lime column and decreases at later period of stabilization due to participation of Ca in pozzolanic reaction. There is also a reduced concentration of other metals due to presence of unfavorable pH medium for metal precipitation and also due to encapsulation of metals by the hydration products.
4. It is also observed that the concentration of other metals is below the threshold limit of IS-10500 and WHO water quality standard.

5. A comparative study between sediment and compacted fly ash bed shows that the hydraulic conductivity values of the specimens of compacted fly ash bed is less than that of the sediment fly ash bed.
6. Based on the experimental findings it can be adjudged that pond ash treated with lime column can be implemented as a reliable and ecofriendly construction material in the Geotechnical applications.

6.3. SCOPE FOR FUTURE WORK

The investigation has certain limitation and hence all the factors that could not be addressed in time. So the future research should incorporate the following aspects in detail.

1. The migration of lime in the ash bed needs to be simulated numerically. Same should be checked in field conditions.
2. Leachate analysis should be done for the elements like As, Hg, Cd, Se and Mn etc. which could not be performed due to non-working of the instruments.
3. Microanalysis of the cured samples should be done by DSC, TGA and mercury intrusion porosity meter.

REFERENCES

1. Adriano, D. C., Page, A. L., Elseewi, A. A., Chang A. C., and Straughan, I. (1980). "Utilization and Disposal of Fly Ash and Other Coal Residues in Terrestrial Ecosystems: A Review."*Journal of Environmental Quality*, 9, 333–344.
2. Amiralian, S., Chegenizadeh, A. and Nikraz, H. (2012)."Investigation on the Effect of Lime and Fly Ash on Hydraulic Conductivity of Soil." *International Journal of Biological, Ecological and Environmental Sciences (IJBEES),* 1(3), ISSN 2277 – 4394.
3. ASTM C 618-89 (1992). "ASTM Standard Specification for Fly Ash and Raw Calcined Natural Pozzolans for Use as a Mineral admixtures in Portland Cement concrete.
4. Behera, B., and Mishra, M. K. (2012). "Microstructure and Leaching Characteristics of Fly Ash - Mine Overburden - Lime Mixtures." *International Conference on Chemical, Civil and Environment Engineering (ICCEE'2012)*.
5. Bin-Shafique, S., Benson, C. H., Edil, T. B., and Hwang, K. (2006). "Leachate concentrations from water leach and column leach tests on fly ash-stabilized soils." *Environ. Eng. Sci.*, 23(1), 53–67.
6. Bishop, P. L. (1988). "Leaching of inorganic hazardous constituents from stabilized/solidified hazardous wastes." *Hazardous Waste & Hazardous Mat.*, 5(2), 129-143.
7. Bowders, J.J., Gidley, J.S., and Usmen, M.A. (1990), "Permeability and leachates characteristics of stabilized class F fly ash." *Transportation research Record*, 1288, Washington, D.C. 70-77.

8. Chand, S. K. and Subbarao, C. (2007). "In-Place Stabilization of Pond Ash Deposits by Hydrated Lime Columns" *Journal of Geotechnical and Geoenvironmental Engineering*, 133 (12), December 1, ASCE, ISSN 1090-0241/2007/12-1609–1616.

9. Cheng, K. Y. (1991). "Controlling Mechanisms of Metals Release from Cement-Based Waste Form in Acetic Acid Solution," PhD dissertation, University of Cincinnati, Cincinnati, Ohio.

10. Choi S. K., Lee S., Song Y. K., Moon H. S.(2002). "Leaching characteristics of selected Korean fly ashes and its implications for the groundwater composition near the ash mound." *Fuel*, 81(8), 1083-1090.

11. Cuisinier, O., Auriol, J., Borgne, T.L., and Deneele, D. (2011). "Microstructure and hydraulic conductivity of a compacted lime-treated soil." *Engineering geology*, 123(3): p. 187-193.

12. Fleming, L.N., Harrison, N.A., and Inyang, H.I. (1996). "Leachant pH Effects on the Leachability of Metals from Fly Ash." *Journal of Soil Contamination,* 5 (1), pp. 53-59.

13. Ghosh, A., and Subbarao, C. (1998). "Hydraulic conductivity and leachate characteristics of stabilized fly ash." *J. Environ. Eng*., 124, 9, 812–820.

14. Ghosh, A., and Subbarao, C. (2001). "Microstructural development in fly ash modified with lime and gypsum.",*J. Mater. Civ. Eng*., 2001.13:65–70.

15. Ghosh, A., and Subbarao, C. (2006). "Leaching of Lime from Fly Ash Stabilized with Lime and Gypsum." *J. Mater. Civ. Eng*., 2006.18:106 – 115.

16. Gottlieb, B., Evans L.S., and Gilbert, S.G. (2010). "Coal ash-The toxic Threat to Our Health and Environment".

17. Gould, J. P., Cross, W. H., and Pohland, F. G. (1989). "Factors influencing mobility of toxic metals in landfills operated with leachate recycle." *Emerging technologies in hazardous waste management.* ACS symposium series. Washington DC. 422, 1989.

18. Guleria, S. P., and Dutta, R. K. (2013). "Durability and Leachate Analysis of Fly Ash - Lime – Gypsum Composition Mixed With Treated Tire Chips." *Journal of GeoEngineering*, 8(2), pp. 33 – 40, August 2013.

19. Hajarnavis, M.R. (2000), "Sudies on trace metals in acidic fly ash." *Journal of scientific and Industrial Research*, 59, pp.381-388.

20. IS 2720: Part 10: 1991 Methods of test for soils: Part 10 Determination of unconfined compressive strength, Bureau of Indian Standards, New Delhi.

21. IS 2720: Part 13: 1986 Methods of Test for Soils - Part 13: Direct Shear Test, Bureau of Indian Standards, New Delhi.

22. IS 2720: Part 17: 1986 Methods of Test for Soils - Part 17: Laboratory Determination of Permeability, Bureau of Indian Standards, New Delhi.

23. IS 2720: Part 4: 1985 Methods of Test for Soils - Part 4: Grain Size Analysis, Bureau of Indian Standards, New Delhi.

24. IS 2720: Part 7: 1980 Methods of Test for Soils - Part VII: Determination of Water Content-Dry Density Relation Using Light Compaction, Bureau of Indian Standards, New Delhi.

25. IS 2720: Part 8: 1983 Methods of Test for Soils - Part 8: Determination of Water Content-Dry Density Relation Using Heavy Compaction, Bureau of Indian Standards, New Delhi.

26. IS 2720: Part III: Sec 2: 1980 Test for Soils - Part III: Determination of Specific Gravity - Section 2: Fine, Medium and Coarse Grained Soils, Bureau of Indian Standards, New Delhi.
27. IS 2720: Part: 1985 Method of Test for Soils - Part 5: Determination of Liquid and Plastic Limit, Bureau of Indian Standards, New Delhi.
28. IS 4332: Part III: 1967 Methods of Test for Stabilized Soils - Part III: Determination of Water Content-Dry Density Relation for stabilized Soil Mixtures, Bureau of Indian Standards, New Delhi.
29. Izquierdo, M., and Querol, X. (2012). "Leaching behaviour of elements from coal combustion fly ash: An overview*." Int. J. Coal Geol*., 94, 54–66.
30. Jankowski, J., Ward, C.R., French, D., Groves, S. (2006). "Mobility of trace elements from selected Australian fly ashes and its potential impact on aquatic ecosystems". *Fuel*, 85, 243–256.
31. Kalinski, M.E., and Yerra, P.K. (2005). "Hydraulic conductivity of compacted cement stabilized fly ash." World of Coal ash (WOCA), April 11-15, 2005, Lexington, Kentucky, USA.
32. Kishan, D., Dindorkar, N. and Shrivastava, R. (2012). "Characteristics of Low Lime Fly Ash Stabilized with Lime and Gypsum," *International Conference on Future Environment and Energy,* IPCBEE Vol. 28 (2012), IACSIT press, Singapore.
33. Lau S.S.S., and Wong W. C. (2001). "Toxicity evaluation of weathered coal fly ash: amended manure compost." *Water Air Soil Pollution*. 128, 243.
34. Lokeshappa, B., and Dikshit, A.K. (2012a). "Single step Extraction of metals in coal fly ash." *Resources and environment*, 2(2), pp. 1-8.

35. Lokeshappa, B., and Dikshit, A.k. (2012b). “Fate of metals in coal fly ash ponds.”*International Journal of Environmental science and development*, 3(1), 43-48

36. Luxa’n, M. P., Sa’nchez de Rojas, M. I., and Fri’as, M. (1989) ‘‘Investigations on the fly ash-calcium hydroxide reactions.’’ *Cement and Concrete Res*., 19(1), 69–81.

37. Method 1311 ,Toxicity Characteristic Leaching Procedure, July 1992

38. Method 3050B , acid digestion of sediments, sludges and soils , December 1996

39. Ozkok, E., Davis, A.P., and Ahmet, A.H. (2013). “Leaching of As, Cr, and Cu from high carbon fly ash soil mixtures.” *Journal of environmental engineering*, 139, pp. 1397-1408.

40. Pal, S.K., and Ghosh, A. (2011). “Compaction and Hydraulic Conductivity Characteristics of Indian Fly Ashes”. *Proceedings of Indian Geotechnical Conference-2011*, 773-776.

41. Prasad, B and Mondal, K. K. (2008). “The impact of filling an abandoned opencast mine with fly ash on ground water quality: A case study.” *Mine Water and the Environment*, **27**(1), 40-45.

42. Sarode, D.B., Jadhav, R.N., Khatik, V.A., Ingle, S.T., and Atarde, S.B. (2010). “Extraction and leaching of heavy metals from thermal power plant fly ash and its admixture.” *Polish j. of Environ. Stud*., 19 (6), pp. 1325-1330.

43. Sengupta, S. and Miller, H. J. (1999). “Preliminary investigation of tire shreds for use in residential subsurface leaching field systems” Chelsea Center for Recycling and Economic Development, Technical Report #12, University of Massachusetts.

44. Shively, W., Bishop, P., and Brown, T. (1986). "Leaching tests of heavy metals stabilized with portland cement." *Water Pollution Control Federation Journal*, 58(3), 234-241.

45. Sridevi, G., Rao, A. S., and Prasad, S. S. V. (2010). "Leaching Studies of Lime-Stabilized Fly Ash Mixes." *Indian Geotechnical Conference – 2010*, 437-440

46. Sushil, S., and Batra, V.S. (2006). "Analysis of fly ash heavy metal content and disposal in three thermal power plants in India."Centre for Energy and Environment, TERI school of Advanced studied, New Delhi.

47. Tran, T.D, Cui, Y., Tang, A. M., Audiguier, M., and Cojean R. (2014). "Effects of lime treatment on the microstructure and hydraulic conductivity of Héricourt clay."*Journal of Rock Mechanics and Geotechnical Engineering*., 6(5), pp. 399-404.

48. Vacovic, V., Trace Element in Coal, Vol.1, pp.59-60, 1983, CRC Press,Inc

49. van der Hoek, E. E., and Comans, R. N. J. (1996). "Modeling arsenic and selenium leaching from acidic fly ash by sorption on iron (hydr)oxide in the fly ash matrix." *Environ. Sci. Technol*., 30(2), 517–523.

50. Vítková, M., Ettler, V., Hyks, J., and Astrup, T. (2010). "Assessment of the leaching behaviour of fly ash from acobalt smelter, Zambia." *Proceedings Venice 2010, Third International Symposium on Energy from Biomass and WasteVenice, Italy; 8-11 November 2010.*

51. Wang, Y., Ren, D., and Zhao, F., (1999). "Comparative leaching experiments for trace elements in raw coal, laboratory ash, fly ash and bottom ash," *Int. J. of Coal Geolog,* 40, pp. 103–108, Jun. 1999.

52. Webster, M. T., and Loehr, R. C. (1996). "Long-term leaching of metals from concrete products," *J. Environ. Eng.*, 122(8), 714–721.

53. Xu, A., and Sarkar, S. L. (1991). ‘‘Microstructural study of gypsum activated fly ash hydration in cement paste.’’ *Cement and Concrete Res.*, 21(6), 1137–1147.

LIST OF PUBLICATIONS

1. Singh, S. P., and Sangita, S. (2015). “Influence of Lime on Hydraulic Conductivity and Leachate Characteristics of Fly Ash.”, *Journal of Civil engineering and Environmental Technology*, Vol. 2, No. 2, pp. 126-130, Jan-March 2015

2. Singh, S. P., and Sangita, S. (2014). “Studies on the leachate characteristics of compacted fly ash bed treated with lime column*.”, I- Manager’s Journal on Structural Engineering,* Vol. 3, No. 2, pp. 21-28, June-August 2014.

3. Singh, S. P.,and Sangita, S. (2015). “Influence of lime on hydraulic conductivity and leachate characteristics of fly ash.” *International Conference on Innovative Trends in Civil Engineering, Architecture and Environmental Engineering for Sustainable Infrastructure Development-2015.*

4. Singh, S. P., Sangita, S., and Ganesh, R. (2014). “Hydraulic Conductivity and Leachate Characteristics of Pond Ash Deposits Treated with Lime Column.” *Indian Geotechnical Conference-2014, pp.* 912-920.

5. Singh, S. P., Sangita, S. and Sahoo, S.P. (2014). “Studies on the Leachate Characteristics of Compacted Fly Ash Bed Treated with Lime Column.” *National Conference on Geotechnical Engineering Practice and Sustainable Infrastructure Development-2014*, pp. 197-206.

6. Singh, S. P., Roy, N., Sangita, S., and Samantasinghar S. (2015). “A Comparative Study On Geo-Technical Characteristics of Sedimented and Compacted Fly Ash Bed Treated with Lime Column.” *Indian Geotechnical Conference-2015***. (Communicated).**

7. Singh, S. P., Roy, N., and Sangita, S. (2015). “Mitigation of Major and Trace Elements Leaching from Pond Ash Deposits by Lime Column Treatment.” *International Journal of Waste Management,* **(Communicated).**